Advanced Transportation System Studies

Technical Area 3

Alternate Propulsion Subsystem Concepts
NAS8-39210
DCN 1-1-PP-02147

Tripropellant Comparison Study
Task Final Report
DR-4
October 1995

ROCKETDYNE

Rockwell International
Rocketdyne Division

Advanced Transportation System Studies

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MSFC/Rocketdyne

Contents

TA3–1133a

Introduction

TA3–0720c

Alternate Propulsion Subsystem Concepts NRA
Option 2 Status

- September 1994 — December 1995
  - Task 1 — Tripropellant Comparison Study
    - $200K
    - Final Briefing October 1995
    - Task Final Report Available
      - Final Briefing Plus Additional Backup
        - Gary Johnson (205) 544-0636
  - Task 2 — Reliability, Maintainability, and Operability Assessment
    - $50K
    - Performed by Rockwell/SSD
    - NASA/MSFC Point-of-Contact
      - Jack Lehner (205) 544-4253
  - Task 3 — Parametric Rocket Engine Cost Modeling
    - $90K
    - RLV Operations Cost Model
    - Parametric Engine Cost Model – Extended Version
    - Due December 1995

TA3–1134

Alternate Propulsion Subsystem Concepts NRA

Tripropellant Comparison Study

Study Objective

- Unbiased, Consistent Data to Draw Out the Inherent Performance Oriented Differences, Benefits and Issues
  - Bipropellant and Tripropellant
  - Engine Implementations

TA3–0762b

Summary

TA3–0720d

Tripropellant Comparison Study
Conclusions

- **For Newly Designed Engines, Using the Same Groundrules and Technology**

- **No Significant Differences in Vehicle Dry Weight Performance Between Tripropellant and Bipropellant Engines**
  - < 3 % Across Chamber Pressure Range 2,000-5,000 psi
    - Bipropellant Engine Slightly Better
  - Single Chamber and Bell Annular Tripropellant Configurations Similar in Vehicle Performance (< 1 %)

- **Much Larger Vehicle Performances Differences Within Any One Engine Configuration Due to Operating Point and Design Choices**
  - Mixture Ratio
  - Chamber Pressure
  - Nozzle Exit Pressure
  - Power Cycle
  - Coated versus Uncoated Materials
  - Welded versus Cast

- **FFSCC Has Significantly Higher Available Margins Than Staged Combustion Cycle (SCC)**
  - For Both Bipropellant and Tripropellant Engines
    - Differences More Pronounced for Tripropellant Engines
  - Inherent Engine Weight Difference ~ 2-5%
    - Favors SCC
    - Applies if Coated Ox Side Or Improved Ox Resistant Materials
  - Strongly Supports the Value of Ox Resistant Material Technology Programs

TA3–1135b

Engine Technical Groundrules

TA3–0868a

Tripropellant Comparison Study

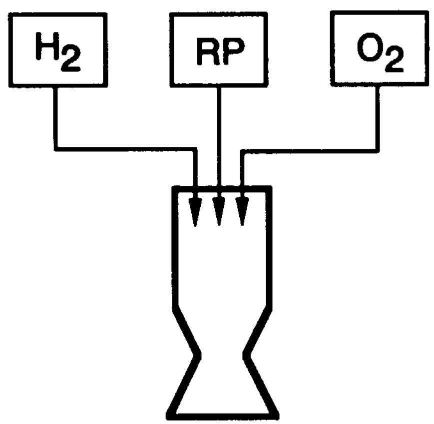
Study Objectives

- Produce an “Apples-to-Apples” Comparison of Tripropellant versus Bipropellant Engines for the SSTO Application
    - Option 3 Vehicle
- Isolate the Effects of Tripropellant versus Bipropellant from the Incidentals of Design Implementation
    - Use the Same Design Groundrules
    - Use the Same Design Practices
    - Include the Same Technologies
- Produce Consistent Bipropellant and Tripropellant Databases Usable for Future Efforts
    - Other Evaluations
    - Other Vehicles
    - Other Applications
    - Support – Other Design Factors
Mission Evaluations

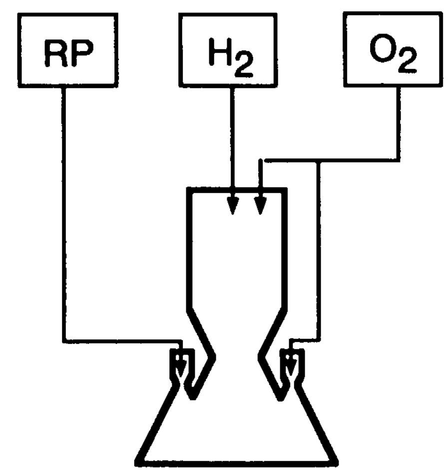
TA3–0718

Tripropellant Configurations

Single Chamber



Annular



TA3–0870b

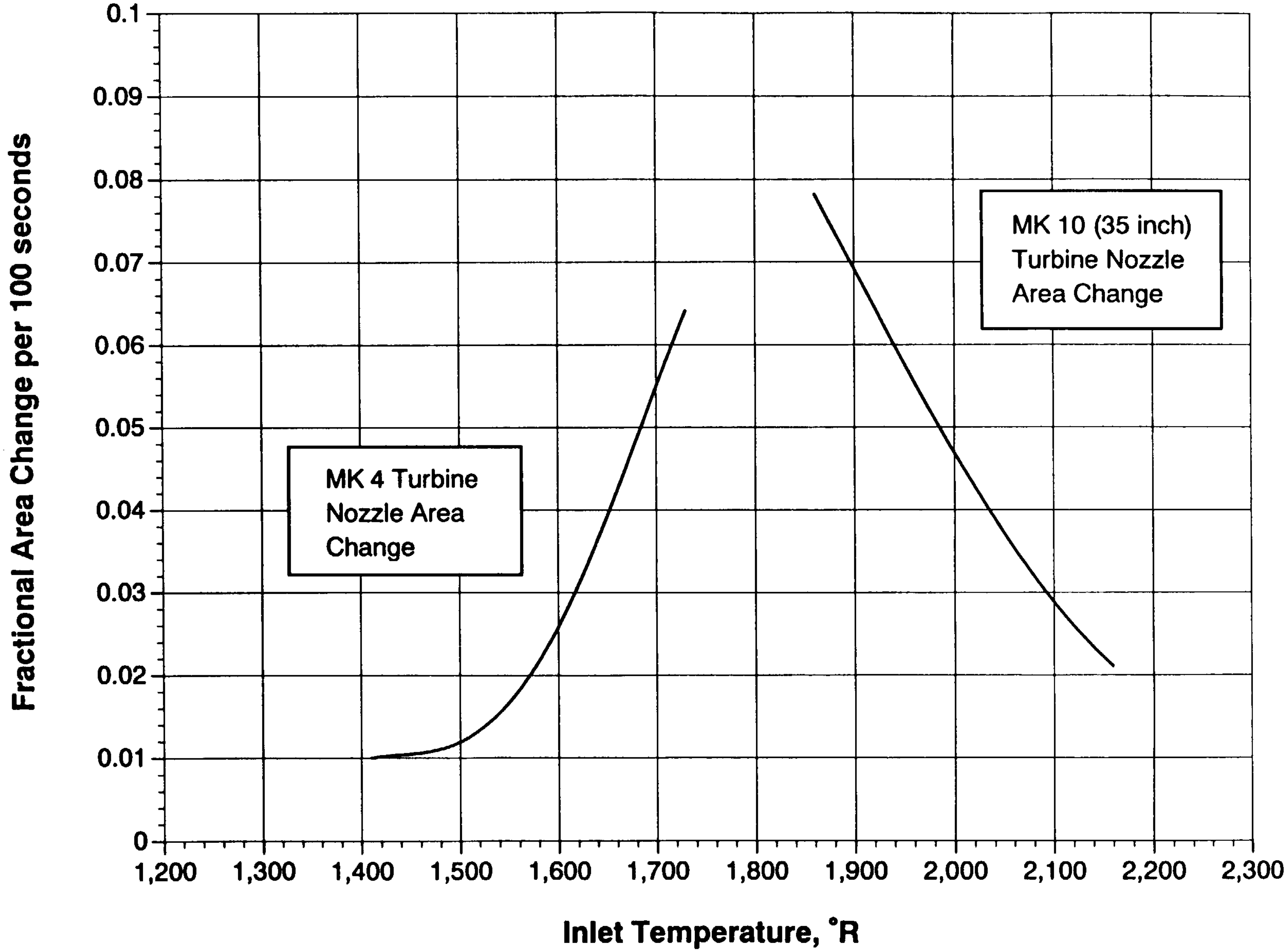
Tripropellant Comparison Study

Engine Groundrules

- Sea Level Thrust – 421,000 lb_f
- Fixed Bell Nozzle
- η_{cstar}
  - O_2/H_2 – 0.995 (@ MR = 6.0)
  - O_2/RP – 0.97 (@ MR = 2.6)
  - O_2/H_2/RP – 0.993 (@ MR = 4.4)
    - At 6% H_2
- Step Loss
  - O_2/H_2 as Inner Chamber
    - 1 percent
  - O_2/H_2 as Outer Chamber
    - 1 percent
- Mixing Loss for Separate O_2/H_2 and O_2/RP Streams
  - O_2/H_2 as Inner Chamber
    - 1 percent
  - O_2/H_2 as Outer Chamber
    - 1 percent
- Individual Thruster Interaction (Annular)
  - 0.985
- Engine Life
  - Number of Missions 60
  - Missions Between Overhauls 20

TA3–0732c

LOX/RP-1 Turbine Nozzle Area Change Characteristics



TA3–0958

Tripropellant Comparison Study
Material Groundrules

- Pumps
    - Al for H_2
    - Inco 718 for O_2 and RP
- Turbines
    - RIM-D1 or Astroloy (Rotor), Thermo-Span (Housing) for H_2 Rich Gases
    - Haynes 214 or Inco 718 for O_2 Rich Gases
    - Inco 718 for RP Rich Gases
        - Astroloy for Rotor if Needed for AN^2 Capability
- Most H_2 Side Components – Thermo-Span
- Most O_2 Side Components – Haynes 214
- Most RP Side Components – Al or Ti
- Injector and MCC Liner – NARloy
- MCC Closeout – Ni/Co
- Nozzles
    - A286 Tubes
    - Ti Honeycomb Jacket
- Silicon Carbide Reinforced Al
    - Thrust Cone and Gimbal Bearing
    - H_2 Valve Bodies
- Composite with Steel Bushings
    - Gimbal Actuator Attach Bracket, Support Struts for Turbomachinery

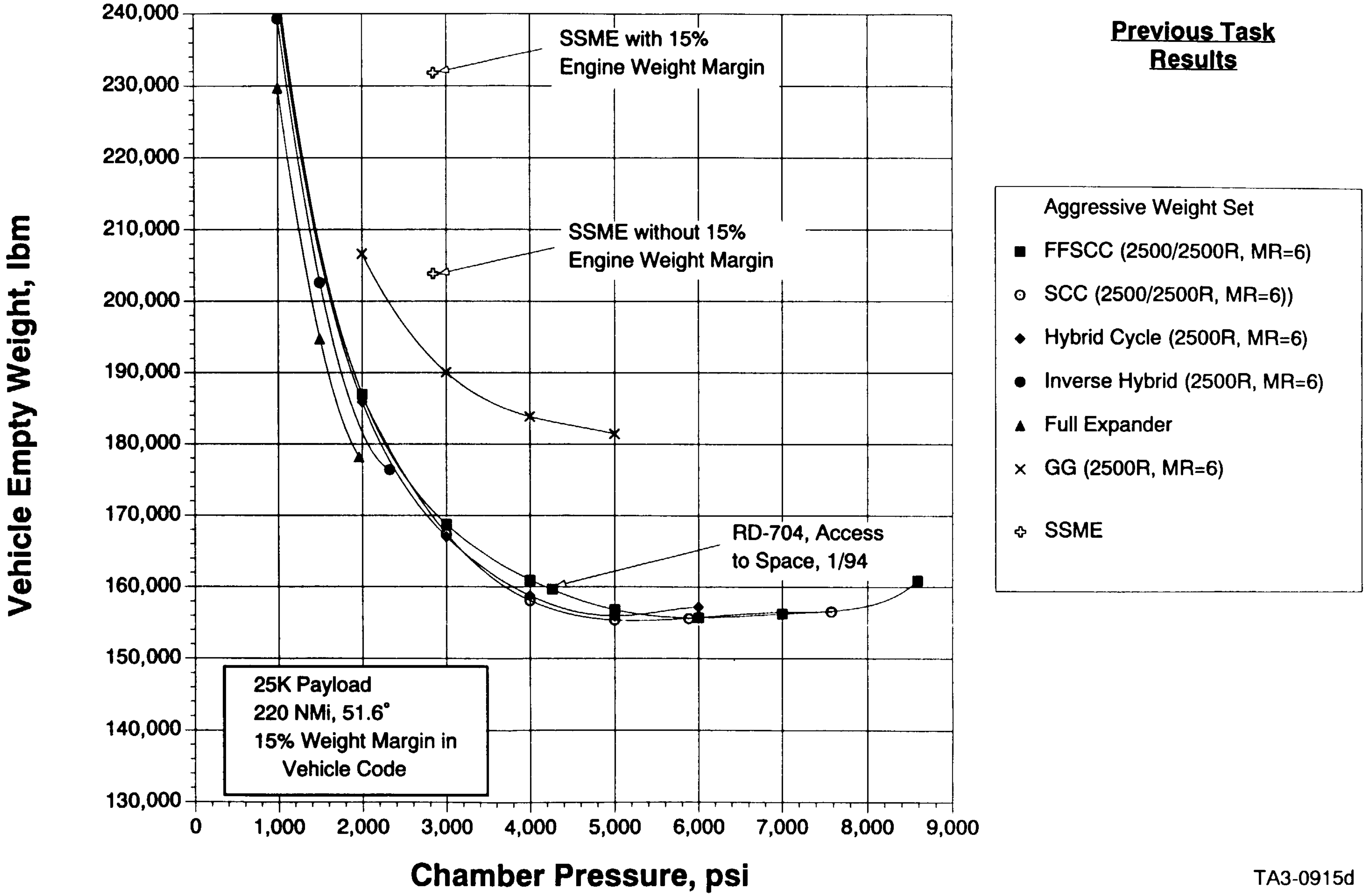
TA3–0731c

Tripropellant Comparison Study
Lessons Learned from Previous Tasks

- From Previous Bipropellant and Tripropellant Efforts
  - Competitive Chamber Pressure $\geq$ 2,000 psi
  - Very High Pressures Possible for Some Closed Cycles but No Vehicle Improvement Above ~ 5,000 - 6,000 psi
  - Performance Penalty for Open Cycles in Mode 2 is Excessive
  - There is an Optimum P_e for a Fixed Nozzle
    - May Differ With Chamber Type
  - Minimal or No Engine Weight Penalty for Lower Turbine Inlet Temperatures
  - Most Important Performance Parameters
    - Sea Level Thrust/Weight
    - Mode 2 Vacuum I_{sp}
    - Mode 1 Vacuum I_{sp}

TA3–0723

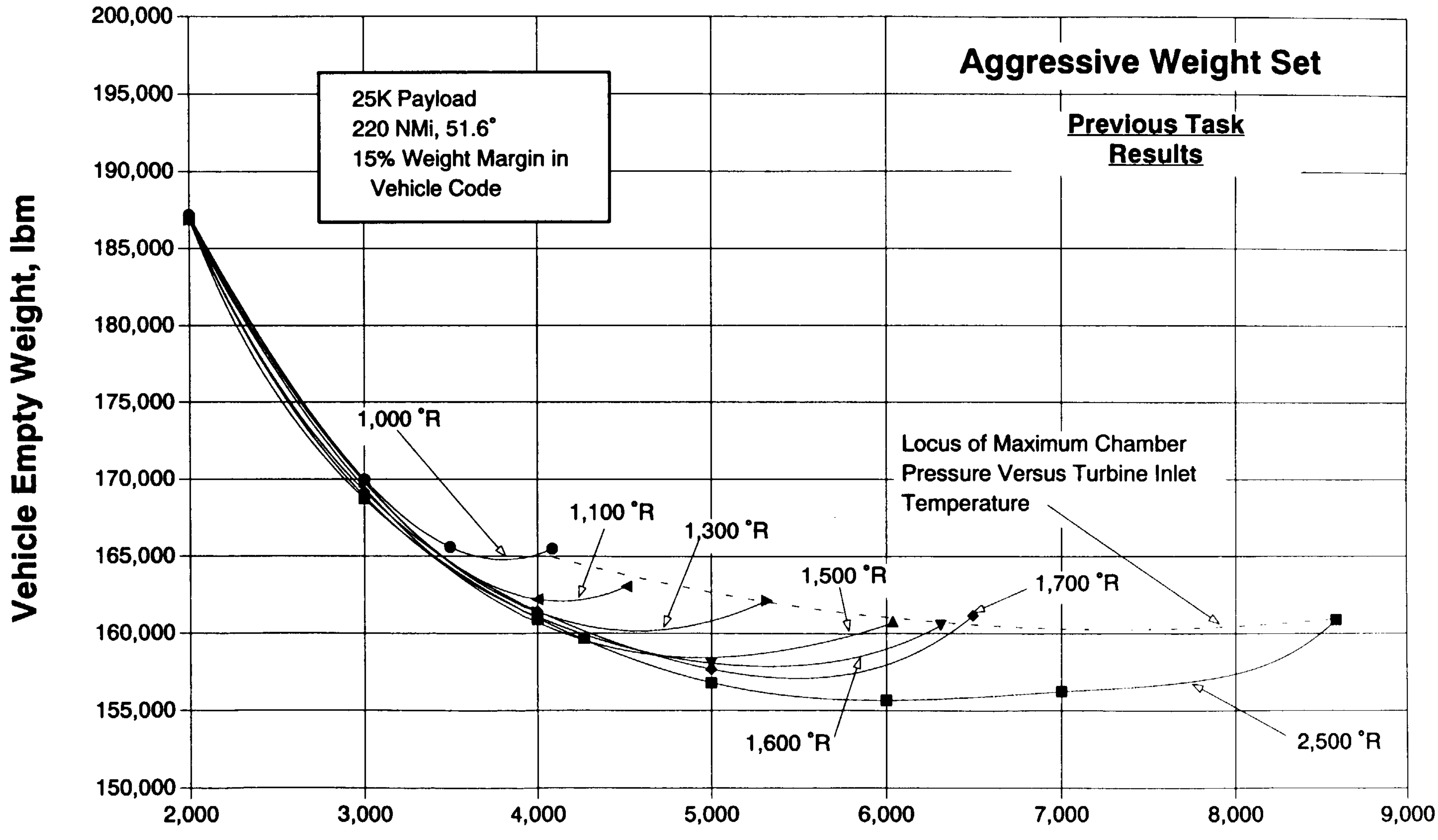
Advanced Low-Cost Engines
SSTO Performance



TA3-0915d

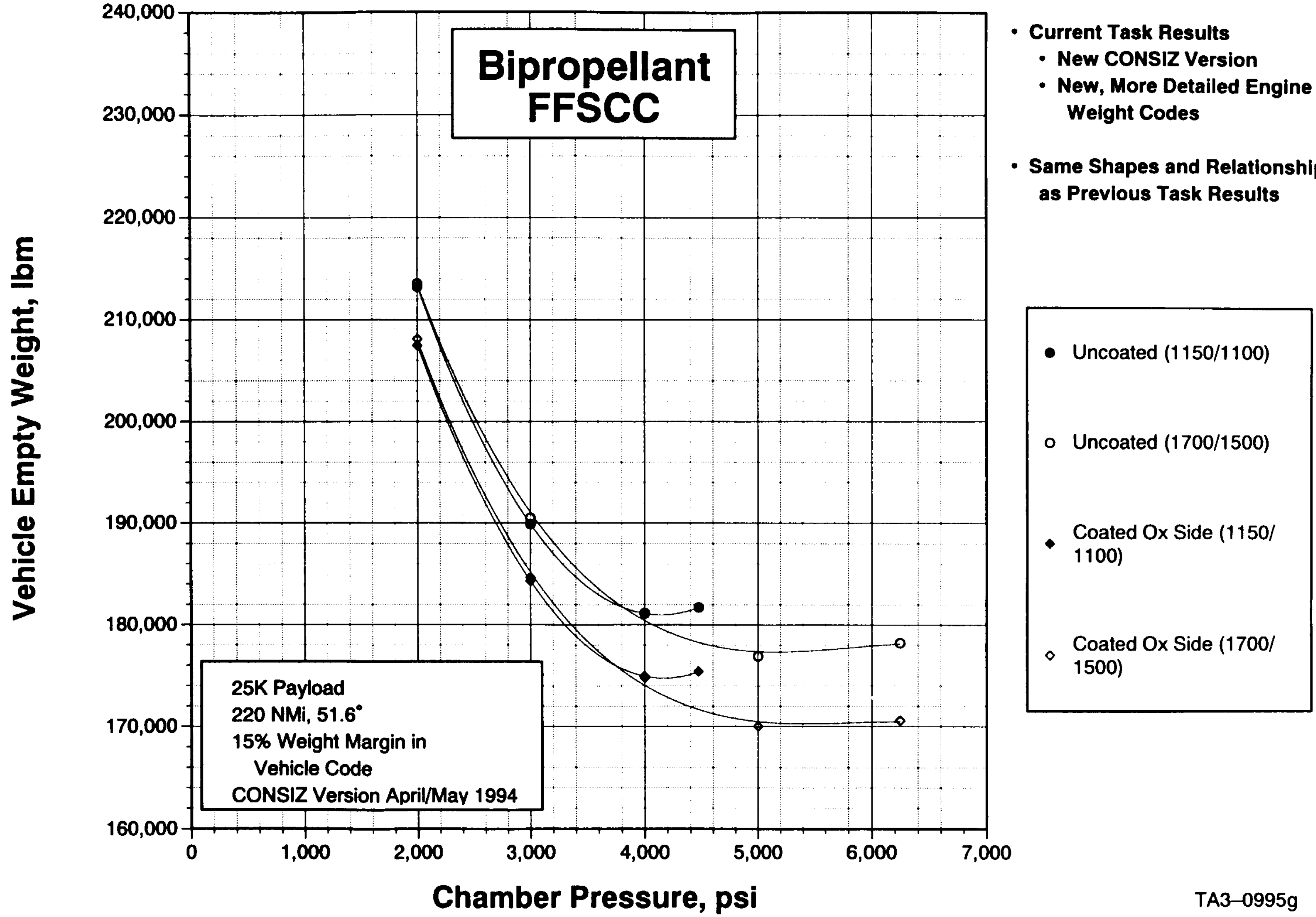
Advanced Low Cost Engines
SSTO Performance
Effect of Fuel Turbine Inlet Temperature

FFSCC



TA3–0910a

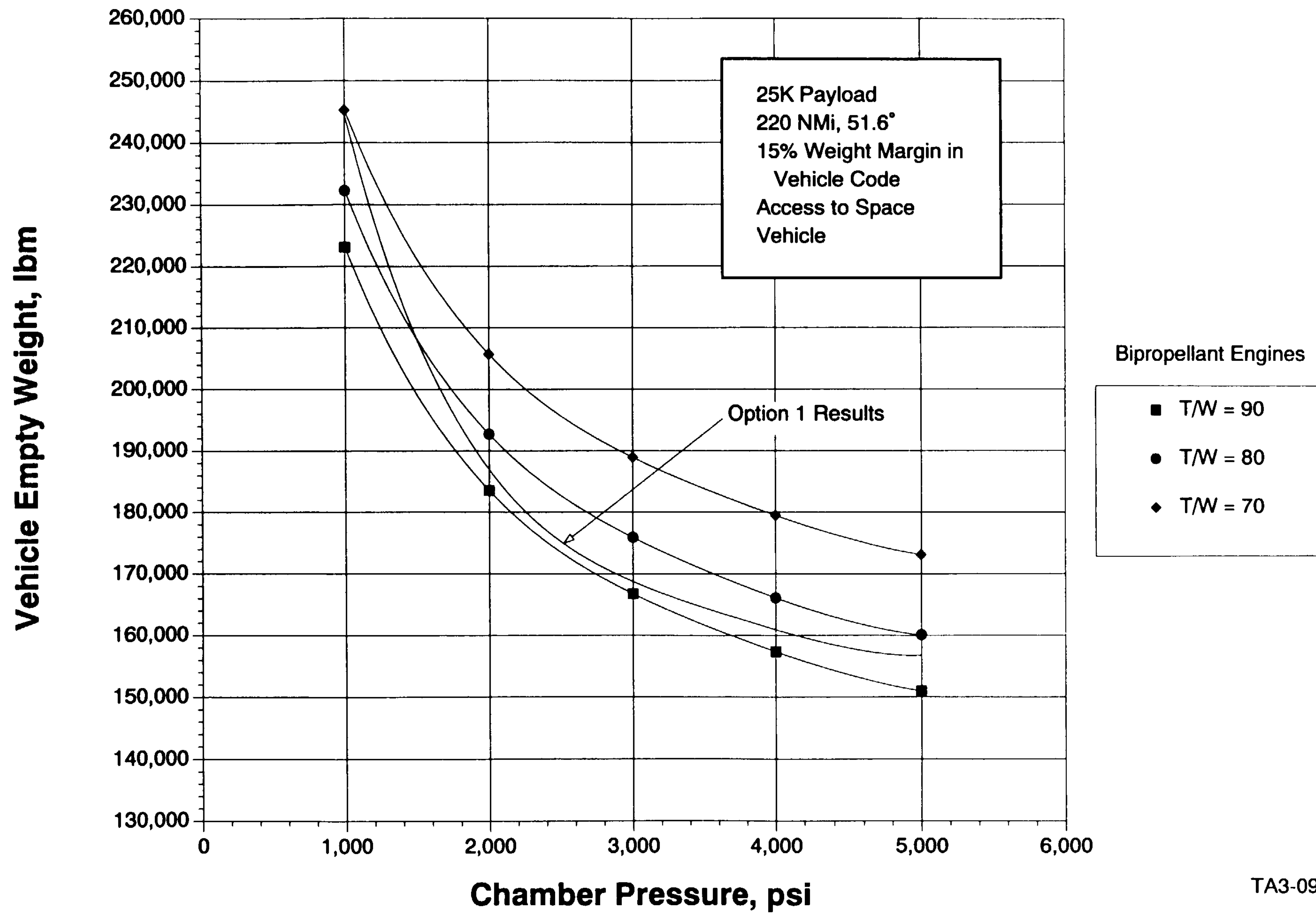
Effect of Turbine Temperature on SSTO Performance



- Current Task Results
  - New CONSIZ Version
  - New, More Detailed Engine Weight Codes
- Same Shapes and Relationships as Previous Task Results

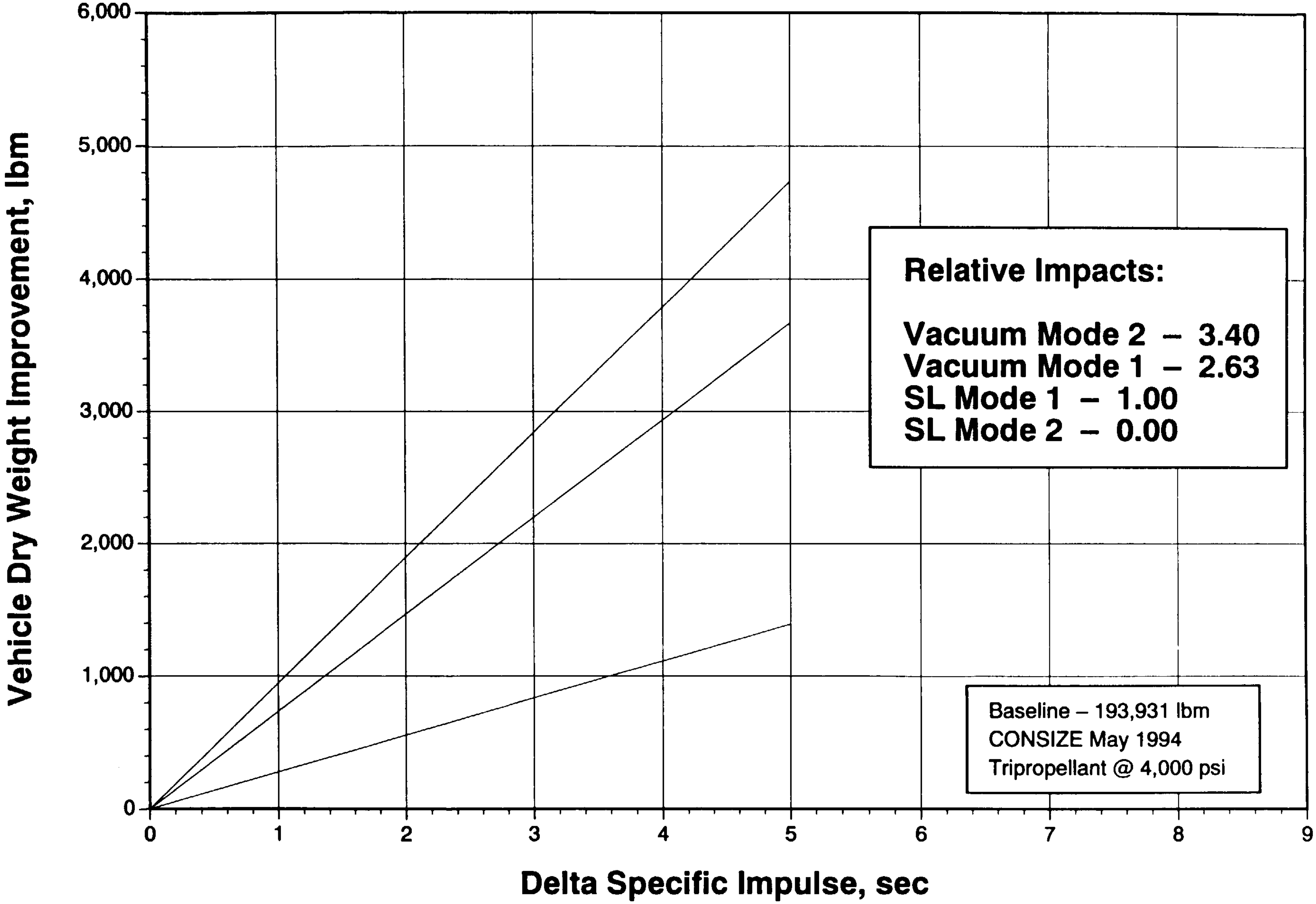
TA3–0995g

Effect of Sea Level Engine T/W on SSTO Performance



TA3-0940

SSTO Performance
Specific Impulse Sensitivities



TA3–0944

Tripropellant Comparison Study
Implications of Lessons Learned

- Chamber Pressures to be Examined
  - $2,000 \leq P_c \leq 6,000$ psi
  - Need Not Examine Low P_c's Nor The Ultimate Power Limit P_c
- Use Minimum Turbine Inlet Temperatures That Are Necessary
  - Consider Exit Gas Properties
  - Consider Pump Discharge Pressures

TA3–0722a

Tripropellant Comparison Study
Operating Parameters

	Single Chamber Tripropellant	Bell Annular Tripropellant	O_2/H_2 Bipropellant
MR (T/C), O_2/H_2; O_2/RP	5.0-7.5; 2.6-3.0	5.0-7.5; 2.6-3.0	5-12
Thrust Split	—	Optimize	—
H_2 Flow (Mode 1/Mode 2)	Optimize	—	—
Mode Switch	Optimize	Optimize	Optimize
P_c, psi	2,000 – 6,000	2,000 – 6,000	2,000 – 6,000
Nozzle	Single Fixed	Single Fixed	Single Fixed
P_{exit}	Optimize One Point Then Fix	Optimize One Point Then Fix	Optimize One Point Then Fix
Sea Level Thrust, lb_f	421,000	421,000	421,000
$T_{turbine}$ (Closed Cycles)	Lowest That Works	Lowest That Works	Lowest That Works
$T_{turbine}$ (GG)	1900 °R	1900 °R	1900 °R

TA3–0735d

Tripropellant Comparison Study
Weight Estimating Procedure

TA3–0857

Alternate Propulsion Subsystem Concepts
Weight Estimating Procedure

- Engines Reflect a Modest Set of New Technologies
    - All Mid-Term or Nearer
    - Not Very Aggressive in Terms of Materials for Weight Reduction

- New Technologies Used in Engines Resulting From Trade Studies
    - Jet Pump Low Pressure Pumps
    - SLIC™ Turbopumps Where Possible
    - Propellant Duct Gimbal Accomodation on Vehicle Side
    - Laser Igniter
    - EMA Valves
    - Materials
        - Al for H_2 Pump
        - Silicon Carbide Reinforced Al
            - Thrust Cone and Gimbal Bearing
            - H_2 Valve Bodies
        - Composite with Steel Bushings
            - Gimbal Actuator Attach Bracket, Support Struts for Turbomachinery
        - Ti Honeycomb Nozzle Jacket
        - Ni/Co Main Combustion Chamber Closeout

TA3–0859

Alternate Propulsion Subsystem Concepts
Weight Groundrules

Materials

- All Material Properties Used are Guaranteed Minimums (Except Al for H_2 Pump)
- 1.2 Limit Load on Pressure then 1.25 on Yield at Operating Temperature
    - More Conservative Than 1.5 on Ultimate
    - Usually More Conservative Than 1.2 Limit Load Followed by 1.5 on Ultimate
    - Most Conservative Method for Materials Used in This Design
- Nozzle Tubes
    - Single Up-pass
    - Nozzle Entrance Mass Flux = 3.0 lbm/(sec-in^2)
    - Material – Annealed A286
    - 1.2 on Yield
        - More Conservative than 1.2 Limit Load Followed by 1.5 on Ultimate
            - 51 ksi versus 68 ksi
- For Components Designed as CATIA Solid Models
    - 1.02 Factor Applied to Weight Because CATIA does not Use Splines
    - 1.05 Factor Applied to Weight for Fillets, welds, etc.

Structural

- Struts to Jet Pumps and Bottom of Turbopumps to Minimize Moments and Other Loads Carried Through Ducts
- Varying Minimum Duct and Cast Wall Thicknesses
    - Ducts
        - 0-2 in ID — 0.030 in
        - 2-3 in ID — 0.045 in
        - 3-6 in ID — 0.060 in
        - > 6 in ID — 0.072 in
    - Castings
        - Calculated Wall Thickness ≤ 0.125 in — 0.125 in
        - Calculated Wall Thickness 0.125 in to 0.250 in — 0.250 in
        - Use Calculated Wall Thicknesses Above 0.250 in

TA3–0861

Alternate Propulsion Subsystem Concepts
Weight Groundrules (Cont'd)

Sizing

- 0.5 in ID Minimum for Any Duct, Line, or Valve
- Liquid Lines Sized for 1.5% Velocity Head Based on Local Pressure
- Gas Lines Sized for 0.14 Mach
    - Except for Manifolds Which are Sized for 0.10 Mach
- Factor of 1.5 Applied to Wall Thickness on Hot Gas Manifolds for Dynamic Loading
- Factors on Ducts and Lines to Match SSME Experience
    - Factor on Calculated Wall Thickness
        - 1.33 for H_2
        - 1.66 for O_2 and RP
    - Factor on Calculated Weight – 1.4 for All Fluids

Misc

- Turbine Bypass Lines on All Turbines (Sized for 20% Preburner Flow)
- Ducts Insulated and Then Covered with Metal Sheath Up to Pumps
- Weight for Purge System (from SSME) for Ground Ops
- Include
    - FASCOS
    - POGO
    - Engine Mounted Controller
    - Line and Nozzle Insulation
    - Nozzle Attachment for Heat Shield
    - Drain Lines with Valves

TA3–0861b

Tripropellant Comparison Study
Weight Estimate Example

TA3–0873

Alternate Propulsion Subsystem Concepts
Weight Estimating Procedure

- Overall Procedure
  - Various Individual Design Procedures Combined at CATIA Assembly Level for Packaging and in Spreadsheet for Weights

- Two Direct Design Procedures are Used

  - CATIA Solid Model (e.g., Hot Gas Manifold)
    - Designed as Individual Component
    - Wall Thickness Calculated
    - Minimums Applied in Model
      - 1.5 Factor for Dynamic Loads Applied to Wall Thickness if Appropriate
    - Solid Volume Returned to Spreadsheet for Weights
    - In Spreadsheet
      - Density used on Solid Volume for Weight
      - 1.02 Factor and 1.05 Factor Applied to Weight

  - CATIA Assembly Model (e.g., Duct)
    - Designed at Assembly Level for Dimensions, Clearances, and Packaging
    - Dimensions Returned to Spreadsheet for Weights
    - In Spreadsheet
      - Wall Thickness Calculated and Minimums Applied
      - Other Subcomponents Calculated (Flanges, Insulation, Insulation Shields, etc.)
      - Weights Calculated from Material Choices and Dimensions
      - Lines and Ducts Corrected to Match SSME Design Practice

- Other Procedures are Used For Some Components and the Procedures May be Combined

  - Scaled (e.g., Valves)
  - Outside Reference (e.g., STME-100 for Controller)
  - Outside Model or Correlation (e.g., SLIC™ Turbomachinery)
  - Directly from SSME (e.g., Static Seals)

TA3–0860

Alternate Propulsion Subsystem Concepts
Weight Calculations

Component (on SSME) (% of SSME Weight) (Listed in Order of SSME Weight)	Procedure		Materials
Turbomachinery (24.7%)			
Fuel Turbopump	Outside Correlation from Adv Rotating Machinery (ARMD93-65)	(H_2)	Pump — Al Turbine — RIM-D1 (Rotor) Thermo-Span (Housing)
		(RP)	Pump – Inco 718 Turbine – Inco 718
Fuel Jet Pump	CATIA Solid Model	(H_2)	Inco 903
		(RP)	Ti-6Al-4V
Ox Turbopump	Outside Correlation from Adv Rotating Machinery (ARMD93-65)		Pump — Inco 718 Turbine — Haynes 214
Ox Jet Pump	CATIA Solid Model		Inco 718
Nozzle (18.7%)	CATIA Solid Model for Manifolds, Mass flux and Spreedsheet for Tubes, Jacket, and Insulation		Tubes — A286 Jacket — Ti Honeycomb Manifolds and Flanges — Thermo-Span Insulation — Nextel Ceramic Fiber Blanket (0.5 area)
Hot Gas Manifolds/Inj/Thrust Cone (13.6%)			
Hot Gas Manifolds			
Fuel	CATIA Solid Model	(H_2)	Thermo-Span
		(RP)	Inco 718
Ox	CATIA Solid Model		Transfer Tube, inlet, Ox Injector Dome — Haynes 214
Injector	CATIA Solid Model		NARloy
Thrust Cone	Scaled from Previous CATIA Solid Model		Silicon Carbide Reinforced Al

TA3–0874

Alternate Propulsion Subsystem Concepts
Weight Calculations (Cont'd)

Component (on SSME) (% of SSME Weight) (Listed in Order of SSME Weight)	Procedure	Materials
Propellant Ducts (11.8%)		
Fuel (Ducts and Flanges)	CATIA Assembly Model	(H_2) Inco 903 (RP) Ti-6Al-4V
Ox (Ducts and Flanges)	CATIA Assembly Model	Inco 718
MCC (6.3%)	CATIA Solid Model (Liquid Interface Diffusion Bonding of Cast Manifolds to Liner)	Liner — NARloy Manifolds and Flanges — Thermo-Span Jacket — E.D. Ni/Co
Valves (5.9%)	Scaled from one Existing EMA Valve and Actuator	
Avionics (5.4%)		
Controller with FASCOS	From STME-100 (22 June 93)	Same as STME
Sensors	From Sensor Suite of STME-100 (22 June 93) Minus ASI Sensor and Three Interpropellant Seal Leak Sensors	Same as STME
Harness	Scaled from STME-100 (22 June 93). Scaled on Physical Size Approximated by $(T_{vac})^{0.5}$	Same as STME
Misc (4.1%)	Scaled as Fraction of System Weight (3.6%). Baseline Percent Determined from SSME	

TA3–0874b

Alternate Propulsion Subsystem Concepts Weight Calculations (Cont'd)

Component (on SSME) (% of SSME Weight) (Listed in Order of SSME Weight)	Procedure	Materials
Preburners (2.8%)		
Fuel Body	CATIA Solid Model (Sizes from External Model)	(H_2) Thermo-Span (RP) Inco 718
Injector	CATIA Solid Model	NARloy
Inlets and Flanges	CATIA Assembly Model	Fuel — Thermo-Span (H_2) Inco 718 (RP) Ox — Inco 718
Ox Body	CATIA Solid Model (Sizes from External Model)	Haynes 214
Injector	CATIA Solid Model	NARloy
Inlets and Flanges	CATIA Assembly Model	Fuel — Thermo-Span (H_2) Inco 718 (RP) Ox — Inco 718
Gimbal Bearing (1.5%)	Scaled from SSME on Material Density	Silicon Carbide Reinforced Al
Lines (Interface: Drain, Repress, and Bleed) (1.4%)		
Fuel	CATIA Assembly Model	(H_2) Inco 903 (RP) Ti-6Al-4V
Ox	CATIA Assembly Model	Inco 718
Pneumatics (1.1%)	Not Used	
POGO (1.1%)	Scaled from SSME (0.25 of Gas)	Same as SSME
Hydraulics (0.4%)	Not Used	
Heat Exchanger (0.4%)	Autogenous Pressurization Using SSME Single Coil Design	
Igniters (0.4%)	Estimate from Combustion Devices	Redundant Laser Igniters
Purge (0.3%)	Direct from SSME	Same as SSME
Bleed Recirc Pumps (0.1%)	Twice the SSME Weight	Same as SSME
Static Seals (0.1%)	Direct from SSME	Same as SSME

TA3–0874c

Alternate Propulsion Subsystem Concepts
Weight Estimate Example and Comparison

- Bipropellant and Single Chamber Tripropellant
- FFSCC
- Design Point
  - Chamber Pressure – 4,000 psi
  - Sea Level Thrust – 421,000 lbf

- Characteristics
  - Fuel Rich Fuel Turbopump
  - LOX Rich LOX Turbopump
  - Jet Pump Low Pressure Pumps
  - Propellant Duct Gimbal Accommodation on Vehicle Side
  - SLIC™ Turbomachinery
  - Uncooled Powerhead
  - EMA Valves
  - Preburner Injectors Gas/Liq Impinging Jet
  - MCC Injectors Gas/Gas Co-Ax
  - Redundant Laser Igniters
  - Autogenous Pressurization on Both Sides
  - Pump Conditioning Fluid Recirculated to Tank on Both Sides

TA3–0858a

Tripropellant Comparison Study

Bipropellant/Tripropellant Engine Parameters

	Bipropellant	Tripropellant (Single Chamber)
Cycle	FFSCC	FFSCC
Area Ratio	70	64
MR – Mode 1	6.9	4.4
MR – Mode 2	6.9	6.2
Chamber Pressure, psi	4,000	4,000
Sea Level Thrust	421,000	421,000
Vacuum Thrust	484,585	477,630
Specific Impulse, sec		
Mode 1 Vac	451.43	406.26
Mode 1 Sea Level	392.19	358.09
Mode 2 Vac	451.43	450.69
Mode 2 Sea Level	392.19	339.18
Mass Flow Fractions, percent		
O2	81.3	81.5
H2	12.7	6.0
RP	—	12.5
Flowrate, lbm/sec		
O2	937.57	957.95
H2	135.88	70.53
RP	—	147.19
Total	1073.45	1175.67
Volume Flowrate, ft3/sec		
O2	12.7	13.0
H2	25.1	13.0
RP	—	2.9
Throat Diameter, inches	8.88	8.78
Turbine Temperature, °R		
O2	1,100	1,100
H2	1,150	1,150
RP	—	1,410

TA3–1155

Tripropellant Comparison Study
Bipropellant/Tripropellant Engine Weights

	Component Weights, lbm				
	Bipropellant		Tripropellant (Single Chamber)		Difference (Biprop-Triprop)
Combustion Chamber		496		485	-11
Nozzle		625		565	-60
Turbopumps		1,061		872	-189
O2	(562)		(563)		
H2	(499)		(222)		
RP	—		(87)		
Preburners		374		364	-10
O2	(344)		(320)		
H2	(40)		(24)		
RP	—		(19)		
Valves		361		349	-12
Ducts		623		665	+42
O2	(358)		(358)		
H2	(265)		(240)		
RP	—		(67)		
Manifolds		460		597	+137
O2	(198)		(189)		
H2	(262)		(228)		
RP	—		(180)		
Controller, Harness, Sensors, Ignition		150		168	+18
Structure		252		258	+6
Misc		165		168	+3
		4,567		4,492	-75

TA3–1154

Tripropellant Comparison Study

Observations on Bipropellant/Tripropellant Engine Weights

- Single Chamber Tripropellant Engine is Not a LOX/RP Engine With a Little H_2
- It Is a High Mixture Ratio LOX/H_2 Engine with Some RP
  - Observe the Volumetric Flows

- Both Engines Have Essentially the Same Throat Area
  - Same Pressure
  - Slightly Higher Flowrate of Tripropellant Burned Gases Offset by Slightly Higher Molecular Weight
  - Effect is That the Chamber and the Nozzle (at the Same Area Ratio) Must Weigh About the Same

- Those Components Most Associated with Volumetric Flows Slightly Favor the Tripropellant
  - Chamber, Preburners, Valves (Main H_2 Valve), and Most Especially the Turbopumps
- Those Components Most Associated with Numbers of Different Flows Slightly Favor the Bipropellant
  - Ducts, Manifolds, Sensors

- Overall, It Should Not be Surprising That the Bipropellant and the Single Chamber Tripropellant Weigh About the Same for the Same Thrust and Chamber Pressure

TA3–1160

Tripropellant Comparison Study
Effect of Engine Weight Changes

- Changes to Design Practices, Groundrules, or Technology Levels
  - Impact Absolute Value, Not Relative Value
    - Engine Weight
    - Vehicle Dry Weight
  - Because Engine Weights and Relative Component Group Weights are Similar

Consequently Such Changes Do Not Impact

Tripropellant/Bipropellant Comparisons

TA3–1156

Advanced Booster Engine 4k Pc O2/H2

Weight Breakdown

- **Vacuum Thrust** 484,585
- **Sea Level Thrust** 421,000
- **H2/O2 Core Pc = 4000** **Nozzle exp. ratio 70**

DUAL MIXED PRE-BURNERS

Main Combustion Chamber							**496**
with injector and liner			CR = 2.92				
			NARloy		NiCo		
Regenerative Cooled Nozzle							**625**
			A-286		Titanium		
Turbopumps							
HPFP	SLIC	**499**	n∏ AL	n∏ AL	Thermo-Span	RIM-D1, A286 TMP	
HPOP	SLIC	**562**	INCO 718	INCO 718	Haynes 214	Haynes 214	**1061**
Pre-Burners							
FPB		**40**			Thermo-Span		
OPB		**334**			Haynes 214		**374**
Valves							**361**
Propellant Ducts							
FUEL		**265**			INCO 903		
includes repress., pump recir., drain, & cryo purge							
OXID		**358**			INCO 718		**623**
includes repress., pump recir., drain, pogo systems, & O2 hxr							
Fuel Hot Gas Manifold					Thermo-Span		**262**
Ox Hot Gas Manifold					Haynes 214		**198**
Controller, Harness, Sensors, & Ignition							**150**
Structure							**252**
Bolts & Misc. parts							**165**
			TOTAL				**4,567 lbs**

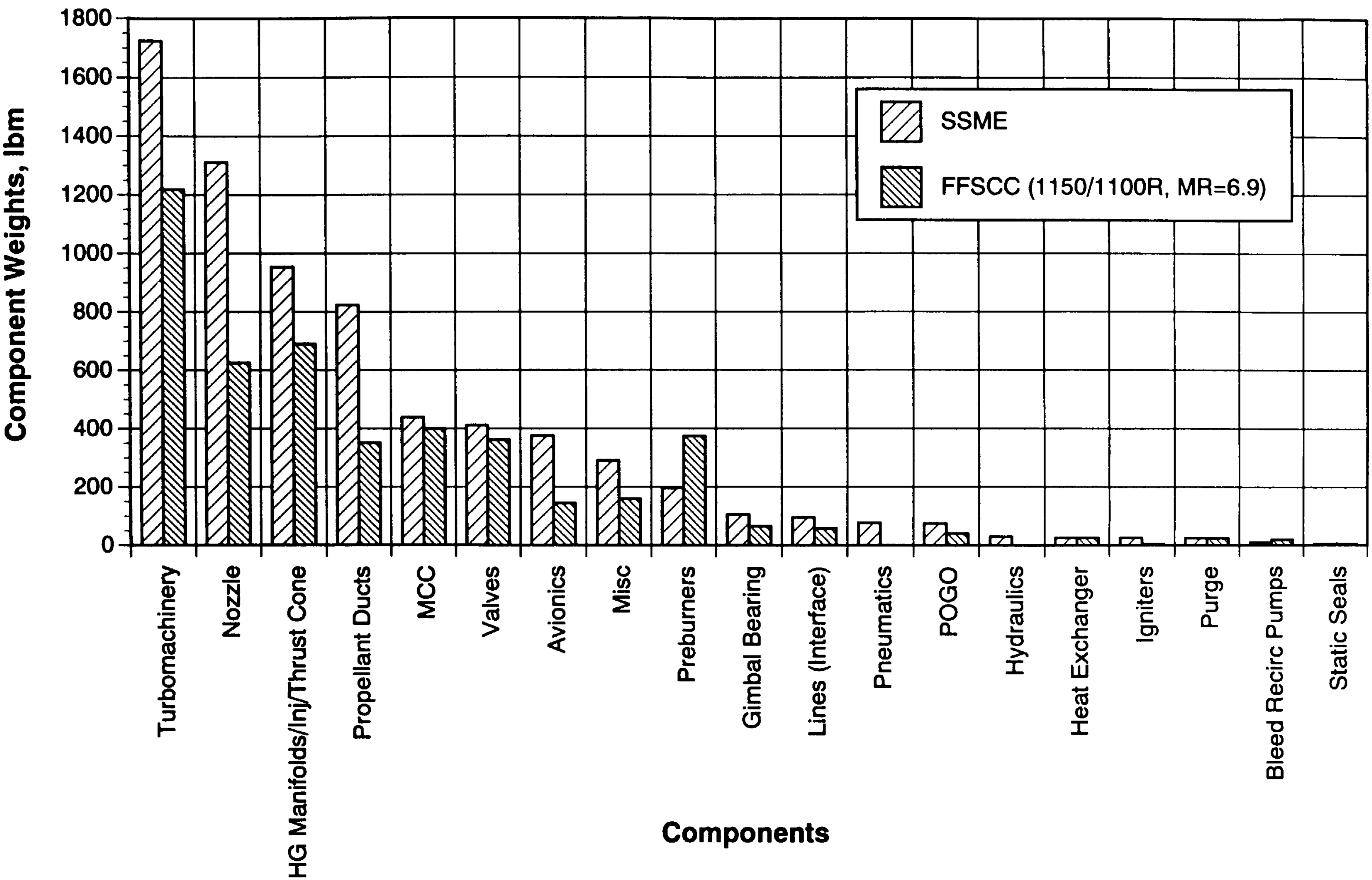
106.10 Tvac/W
92.18 Tsl/W

Alternate Propulsion Subsystem Concepts
Weight Estimate Example
Weight Comparison to SSME

Component Area	SSME Weights, lbm	Adv Low Cost Eng Weights, lbm	Difference lbm	Rationale
Turbomachinery	1,725.00	1,218.67	(506.33)	SLIC™, Jet Pumps, mixture ratio
Nozzle	1,310.54	625.30	(685.24)	Essentially same weight on equal surface area basis (1,371), Ti honeycomb jacket, lower hydrogen flowrate
Hot Gas Manifolds/Inj/ Thrust Cone	953.00	689.76	(263.24)	
Propellant Ducts	822.91	351.12	(471.79)	Gimbal flex accommodation on vehicle side, Jet Pump, shorter lines and routing, mixture ratio
MCC	438.54	399.71	(38.83)	
Valves	410.62	361.35	(49.27)	Uses EMA Valves. Includes Valves and Actuators
Avionics	375.00	143.64	(231.36)	Controller with FASCOS
Misc	289.30	158.71	(130.59)	Proportional to weight (3.6%)
Preburners	195.75	373.99	178.24	Ox rich operation, both flows as gas
Gimbal Bearing	105.00	65.32	(39.68)	From Ti to Si carbide reinforced Al
Lines (Interface)	95.32	56.75	(38.57)	Simplified routing, combined recirc and repressurization, less drain
Pneumatics	76.90	0	(76.90)	EMA valves
POGO	75.13	40.65	(34.48)	Stiffer System, 25% SSME gas
Hydraulics	30.32	0	(30.32)	EMA Valves
Heat Exchanger	26.00	26.00	0	Part of LOX rich preburner
Igniters	26.00	6.00	(20.00)	Laser Igniters
Purge	24.39	24.39	0	Left in for ground Ops
Bleed Recirc Pumps	10.00	20.00	10.00	Add to LOX side
Static Seals	6.00	6.00	0	
	6,995.72	4,567.36	(2,428.36)	

TA3–0862

Weight Comparison by Component Area



TA3–0957

Tripropellant Comparison Study
Choice of Weight Baseline

TA3–0856

Alternate Propulsion Subsystem Concepts
Choice of Weight Baseline
Approaches

- Approaches to Manufacturing and Operations Can Significantly Affect Engine Weight

- Current State-of-the-Practice
  - Coatings for Turbines
  - Welded Construction

- Approaches
  - Minimize Welds – Use Castings
    - Lower Strength Material Properties – Increased Weight
  - Use Materials Which Do Not Need Coatings
    - Poorer Material Properties
      - Lower AN^2 Limit – Lower T/P RPM, Increased Weight
      - Lower Strength – Increased Weight
    - RIM-D1 for H_2 Rich Turbine Rotor
    - Thermo-Span for H_2 Rich Turbine Housing, Hot Gas Manifold, Preburner Body
      - Welded
    - Haynes 214 or Inco X-750 for O_2 Rich Turbine Rotor, Housing, Hot Gas Manifold, Preburner Body
      - Cast or Welded

TA3–0871a

Tripropellant Comparison Study
Sample Case for Design Practice Study

- Bipropellant
- FFSCC
- MR = 6.0
- Nozzle Exit Pressure = 4.0
- Turbine Temperatures
  - Fuel — 1100°R
  - Oxidizer — 1100°R

TA3–1136

Weight Baseline – Design Choice Effects

5,184 lbm — No Coatings (Haynes 214)
- Max Cast**

5,065 lbm — No Coatings (Inco X-750)
- Max Cast**

5,054 lbm — Coated*
- Max Cast**

4,781 lbm — No Coatings (Haynes 214)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,662 lbm — No Coatings (Inco X-750)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,662 lbm — Some Coatings
- Ox Turbine Rotor
  Ox Turbine Housing
- Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,552 lbm — Some Coatings
- Ox Turbine Rotor
  Ox Turbine Housing
- Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing
  Ox Hot Gas Manifold
  Ox Preburner

4,461 lbm — Coated, Welded
Fuel Side Not Coated

4,391 lbm — Coated*, Welded

Current State-of-the-Art
and Practice

Note:

Baseline Engine: Full Flow Mixed Preburner
Cycle, Bipropellant O_2/H_2, P_c = 4,000 psi,
Nozzle Exit Pressure = 4 psi, MR = 6.0

* Coated Components
Turbine Rotor
Turbine Housing
Hot Gas Manifold
Preburner

** Fuel Turbopump Not Cast

TA3–0892b

Weight Baseline – Design Choice Effects

5,184 lbm — No Coatings (Haynes 214)
- Max Cast**

5,065 lbm — No Coatings (Inco X-750)
- Max Cast**

5,054 lbm — Coated*
- Max Cast**

4,781 lbm — No Coatings (Haynes 214)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

Chosen Baseline

4,662 lbm — Some Coatings
- Ox Turbine Rotor
  Ox Turbine Housing
- Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,662 lbm — No Coatings (Inco X-750)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,660 lbm — No Coatings (Si_3N_4)
- Max Cast **

4,552 lbm — Some Coatings
- Ox Turbine Rotor
  Ox Turbine Housing
- Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing
  Ox Hot Gas Manifold
  Ox Preburner

4,461 lbm — Coated, Welded
Fuel Side Not Coated

4,391 lbm — Coated*, Welded

Current State-of-the-Art
and Practice

4,256 lbm — No Coatings (Si_3N_4)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,090 lbm — No Coatings (Si_3N_4)
- Some Welded: Fuel T/P
  Coolant Manifolds
  LOX Pump Housing
- Si_3N_4 Used for Fuel
  and Ox Hot Gas Manifolds
  and Preburners

3,661 lbm — No Coatings (Si_3N_4)
- Max Cast**
- Si_3N_4 Used for Fuel and
  Ox Ducting and Preburners

Note:
1,523 lbm Weight Delta (+18.1%, -16.6%)
Represents a ~17% Dry Vehicle Weight Band

Baseline Engine: Full Flow Mixed Preburner
Cycle, Bipropellant O_2/H_2, P_c = 4,000 psi,
Nozzle Exit Pressure = 4 psi, MR = 6.0

* Coated Components
Turbine Rotor
Turbine Housing
Hot Gas Manifold
Preburner

** Fuel Turbopump Not Cast

TA3–0892

Weight Baseline – Design Choice Effects

5,184 lbm
No Coatings (Haynes 214)
- Max Cast**

5,065 lbm
No Coatings (Inco X-750)
- Max Cast**

5,054 lbm
Coated*
- Max Cast**

4,781 lbm
No Coatings (Haynes 214)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,662 lbm
Some Coatings
- Ox Turbine Rotor
  Ox Turbine Housing
- Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,662 lbm
No Coatings (Inco X-750)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,660 lbm
No Coatings (Si_3N_4)
- Max Cast **

4,552 lbm
Some Coatings
- Ox Turbine Rotor
  Ox Turbine Housing
- Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing
  Ox Hot Gas Manifold
  Ox Preburner

4,461 lbm
Coated, Welded
Fuel Side Not Coated

4,391 lbm
Coated*, Welded

Current State-of-the-Art
and Practice

4,256 lbm
No Coatings (Si_3N_4)
- Some Welded: Fuel T/P
  Fuel Preburner
  Fuel Hot Gas Manifold
  Coolant Manifolds
  LOX Pump Housing

4,090 lbm
No Coatings (Si_3N_4)
- Some Welded: Fuel T/P
  Coolant Manifolds
  LOX Pump Housing
- Si_3N_4 Used for Fuel
  and Ox Hot Gas Manifolds
  and Preburners

3,661 lbm
No Coatings (Si_3N_4)
- Max Cast**
- Si_3N_4 Used for Fuel and
  Ox Ducting and Preburners

Note:

Baseline Engine: Full Flow Mixed Preburner
Cycle, Bipropellant O_2/H_2, P_c = 4,000 psi,
Nozzle Exit Pressure = 4 psi, MR = 6.0

* Coated Components
Turbine Rotor
Turbine Housing
Hot Gas Manifold
Preburner

** Fuel Turbopump Not Cast

TA3–0892c

Alternate Propulsion Subsystem Concepts
Engine Weight – Design Choice Effects

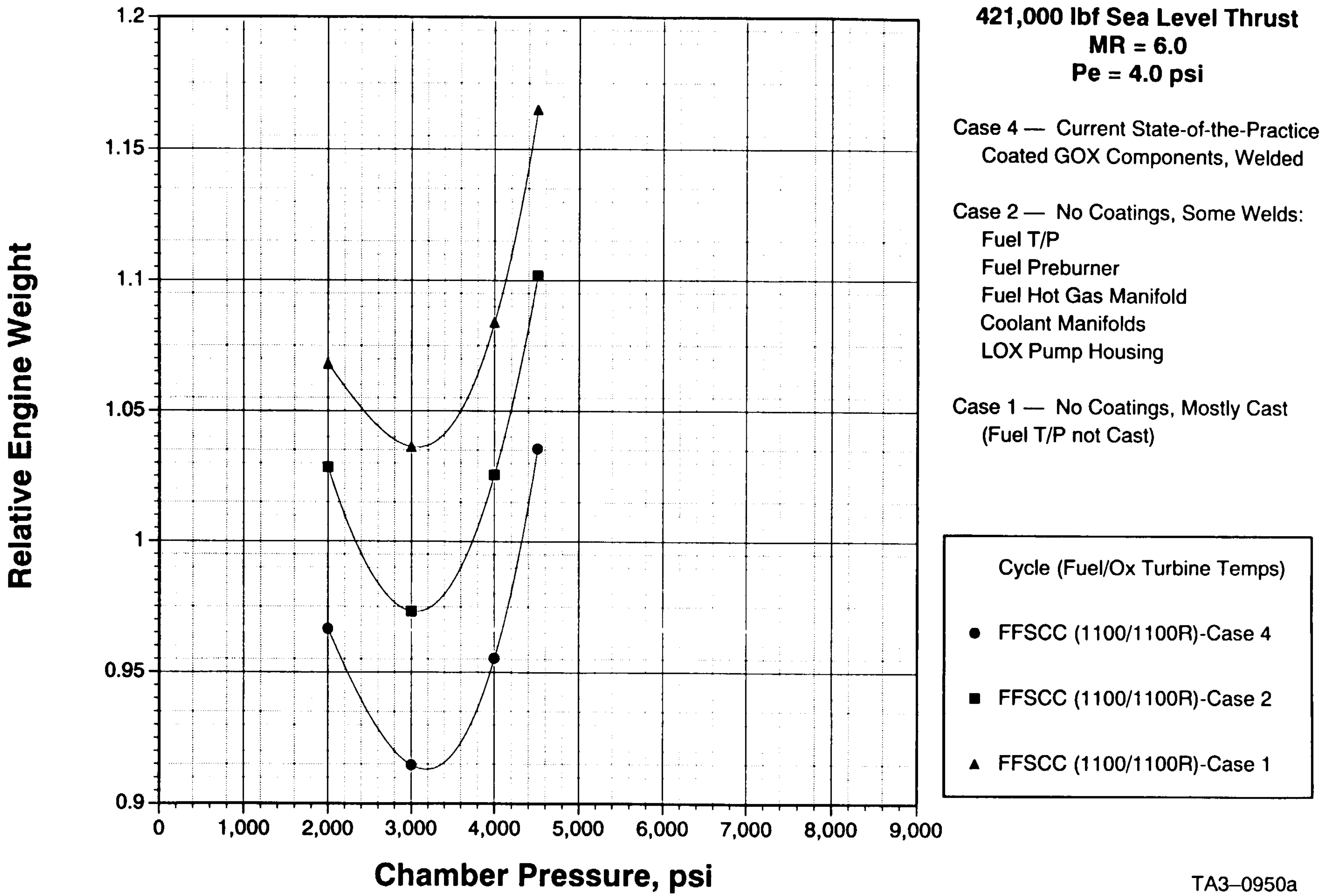
		Weight	Delta Weight
Current Practice (Welded, Coated)		4,391 lbm	
No Fuel Coatings, Welded		4,461 lbm	+ 70 lbm
Cast,	No Fuel Coatings	5,054 lbm	+ 663 lbm
	No Fuel or Ox Coatings – Haynes 214	5,184 lbm	+ 793 lbm
	No Fuel or Ox Coatings – Inco X-750	5,065 lbm	+ 674 lbm
Welded,	No Fuel or Ox Coatings – Haynes 214	4,781 lbm	+ 390 lbm
	No Fuel or Ox Coatings – Inco X-750	4,662 lbm	+ 271 lbm

	Weight Penalty	
Welded		
Fuel Uncoated	70 lbm	1.6%
Ox Uncoated – Haynes 214	314 lbm	7.2%
Ox Uncoated – Inco X-750	195 lbm	4.4%
Fuel and Ox Uncoated – Haynes 214	390 lbm	8.9%
Fuel and Ox Uncoated – Inco X-750	271 lbm	6.2%
Maximum Use of Castings		
Coated	638 lbm	14.5%
Fuel Uncoated	663 lbm	15.1%
Ox Uncoated – Haynes 214	768 lbm	17.5%
Ox Uncoated – Inco X-750	649 lbm	14.8%
Fuel and Ox Uncoated – Haynes 214	793 lbm	18.1%
Fuel and Ox Uncoated – Inco X-750	674 lbm	15.3%

Bipropellant, FFSCC, 4000 psi Chamber Pressure, MR = 6, P_e = 4 psi

TA3–0897

Bipropellant O_2/H_2 Engines
Engine Weights – FFSCC



421,000 lbf Sea Level Thrust
MR = 6.0
Pe = 4.0 psi

Case 4 — Current State-of-the-Practice
Coated GOX Components, Welded

Case 2 — No Coatings, Some Welds:
Fuel T/P
Fuel Preburner
Fuel Hot Gas Manifold
Coolant Manifolds
LOX Pump Housing

Case 1 — No Coatings, Mostly Cast
(Fuel T/P not Cast)

TA3–0950a

Alternate Propulsion Subsystem Concepts
Choice of Weight Baseline
Conclusions

- Use Materials Which Do Not Need Coatings for H_2 Rich Gases
  - Major Operations Gain, Minimal Weight Penalty

- Use Materials Which Do Not Need Coatings for O_2 Rich Gases
  - Operations Improvement Too Important to Not Use
  - Significant Weight Penalty

- Use Welded Construction for Many Parts
  - Only Way to Recover Part of the No Coating Weight Penalty

- Si_3N_4 as Structural Material for Ducts and Housings
  - Not Used in Current Baseline
    - Too Far in Future

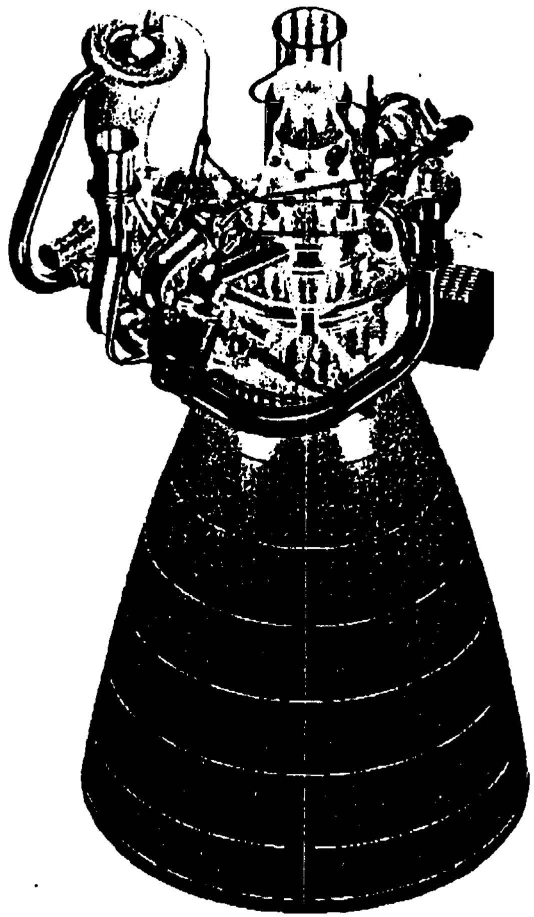
- Pursue Technology Programs to Increase the Strength of Oxygen Resistant Materials
  - Appears Very Feasible

TA3–0872

Cycle Options
and
Turbopump Arrangements

TA3–0737

Tripropellant Comparison Study
Currently Proposed Engines



- No Currently Proposed Tripropellant Engine Represents an Optimized Clean Sheet of Paper Tripropellant Engine Design
  - All Attempt to Use Some Existing Hardware or Are Derived From, and Thus Constrained by, Existing Engines
    - RS-2000
    - RD-704
    - RD-0120TP
- A Clean Sheet Design Will Not Necessarily Resemble Any of Them

TA3–0739

Alternate Propulsion Subsystem Concepts
Closed Cycle Thermodynamic Capabilities

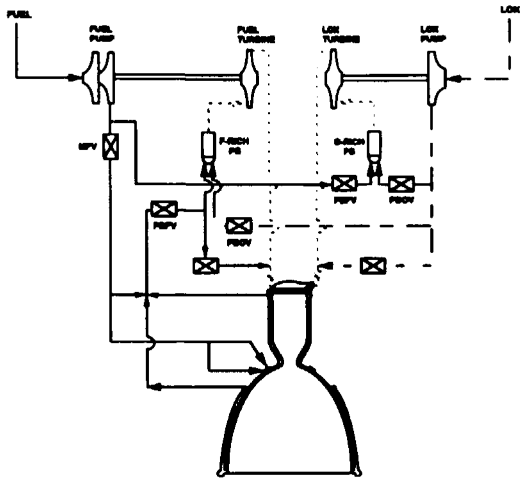
Cycle	Added Energy (Combustion)		Flows Used		Expected Propulsion Weight
	Fuel Side	Oxidizer Side	Fuel	Oxidizer	
Dual, Mixed Preburners	√	√	√	√	Highest
Dual, Fuel (or Ox) Rich Preburners	√	√	√	Part	
Single Preburner/ Expander	√	—	√	Part	
Single Preburner Expander	—	√	√	Part	
Expander	—	—	√	None	Lowest

TA3–0519

Bipropellant Engine Cycles

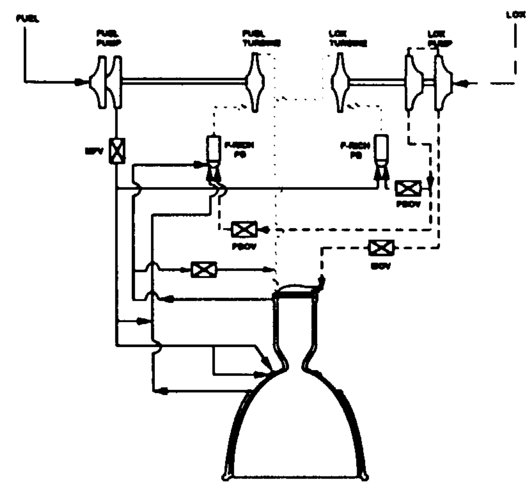
FFSCC Mixed Preburner Engine

Regen Cooled MCC and Nozzle



SCC Dual Fuel-Rich Preburner Engine

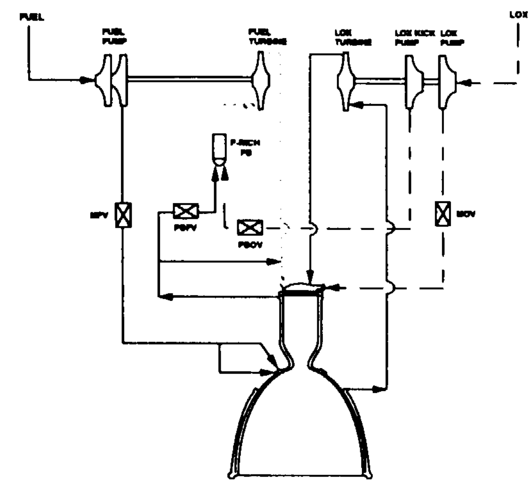
Regen Cooled MCC and Nozzle



Hybrid Cycle Engine

(Fuel Side Preburner, Ox Side Expander)

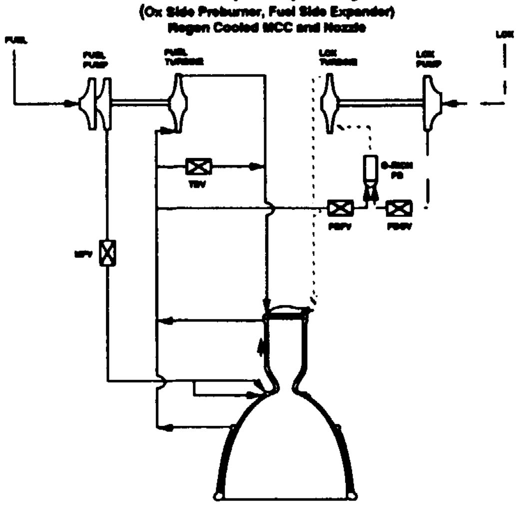
Regen Cooled MCC and Nozzle



Inverse Hybrid Cycle Engine

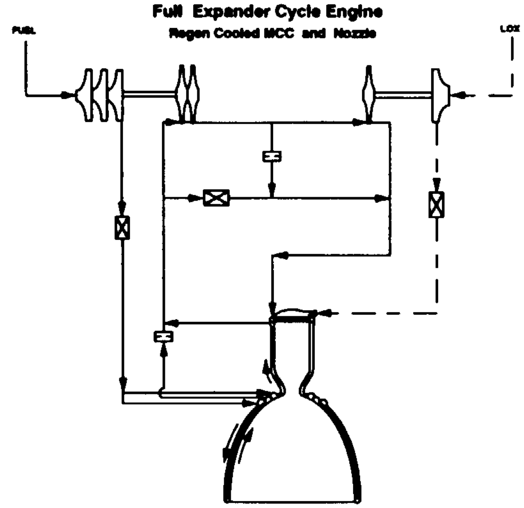
(Ox Side Preburner, Fuel Side Expander)

Regen Cooled MCC and Nozzle



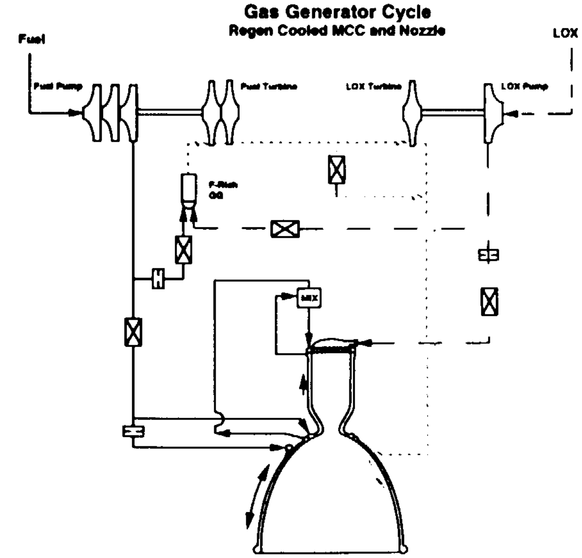
Full Expander Cycle Engine

Regen Cooled MCC and Nozzle



Gas Generator Cycle

Regen Cooled MCC and Nozzle



Tripropellant Comparison Study
Potential Engine Cycles

- Closed Cycles
    - FFSCC
        - Uses Both Fuel Rich and Ox Rich Preburners
    - SCC
        - Uses Either Fuel Rich Or Ox Rich Preburners, Not Both
    - Hybrid Cycle
        - Uses Fuel Rich Preburner for Fuel Side and Expander for Ox Side
    - Inverse Hybrid
        - Uses Ox Rich Preburner for Ox Side and Expander for Fuel Side
    - Expander
        - Uses Expander for Both Fuel and Ox Sides

- Open Cycles
    - GG
        - Uses a Gas Generator for Both Fuel and Ox Sides

TA3–0745

Tripropellant Comparison Study

Potential Engine Cycles

- For a Tripropellant Engine These Cycles can be Mixed
  - Different Cycles Can be Used for the O_2/RP System than for the O_2/H_2 System
  - Additionally Various Turbopumps and Preburners/GGs Can be Shared Between the O_2/RP and the O_2/H_2 Systems
- Consequently the Number of Potential "Cycles" is Very Large
- Since the Study Objective is to Compare the Best Potential Tripropellant Implementations to the Best Potential Bipropellant Implementations
  - The Study Will be Limited to Only Those Cycles with the Best Expected Combination of Specific Impulse and Engine Weight

TA3–0745a

Tripropellant Comparison Study
Basic Cycle Choices

- From the Separately Reported Bipropellant Study Completed Earlier in the Contract
  - Without Engine Margin Considerations
    - Three Cycles Competitive
      - FFSCC
      - SCC
      - Hybrid
    - Two Cycles Maximum Chamber Pressure ~2,000 psi
      - Inverse Hybrid
      - Expander
    - Common Thread
      - Cycles with the Highest Horsepower Pumps Driven by Expander Cycle Cannot Reach Competitive Chamber Pressures
        - Power Limited at Too Low a P_c
  - With Engine Margin Considerations
    - FFSCC Very Robust
    - Fuel Rich SCC Turbine Temperatures Become High
    - Hybrid Cycle Turbine Temperatures Marginal Even Before Margins

- Conclusion
  - Examine Only FFSCC, SCC, and Hybrid
    - Hybrid Only With H_2 Driven RP Pump

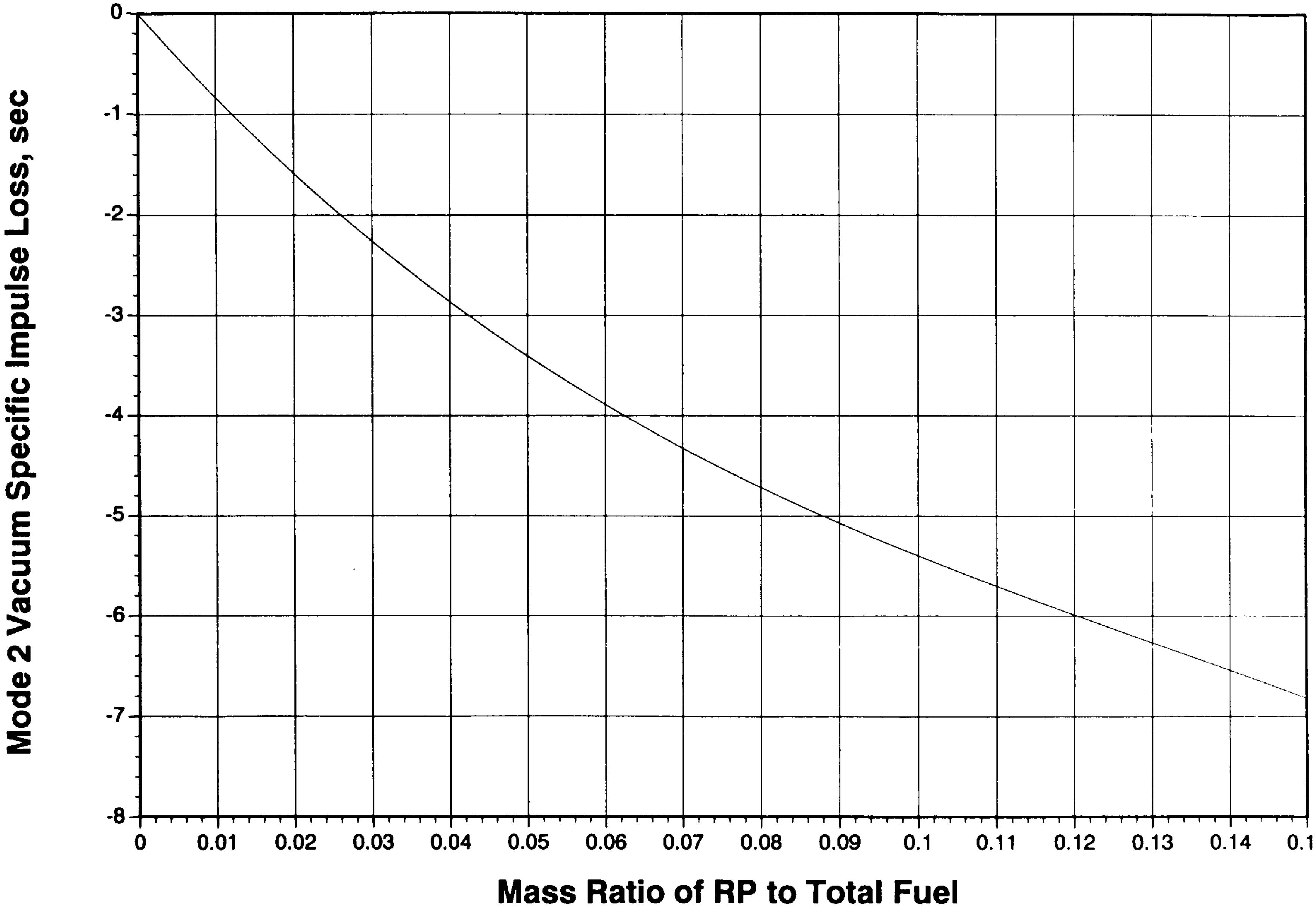
TA3–0740a

Tripropellant Comparison Study
Cycle Considerations

- Primary Performance Parameters
  - Engine Sea Level Thrust/Weight
  - Mode 2 Vacuum Specific Impulse
  - Mode 1 Vacuum Specific Impulse
- All Cycle Selection Choices Should be Based on Their Impact on These Parameters
- One Simplifying Limitation
  - No RP in Mode 2
    - I_{sp} Loss in Mode 2
    - No Sea Level Weight Improvement Except in Single Preburner Case
      - Then Probably Offset by Additional Ducting and Hot Gas Valves

TA3–0738

SSTO Performance
Impact of RP in Mode 2



TA3–0943

Tripropellant Comparison Study
Numbers of Preburners

- **All Staged Combustion Cycles Can Have Up to Four Preburners**
- **FFSCC Must Have at Least Two Preburners**
- **SCC Can Have as Few as One Preburner for the Whole Engine**

Preburner Configuration	Pros	Cons
One Per Turbine	Less Hot Gas Ducting More Flexible Packaging Avoid Hot Gas Valves Better Control Avoids Additional Complexity of Tripropellant Preburner While Minimizing Turbine Temps Possibly Least Weight	More Preburners More, Smaller Feed Valves More Complex Start
One per Engine	Less Preburners Less Feed Valves Less Complex Start	More Hot Gas Ducting Less Flexible Packaging Hot Gas Valves More Difficult Control For Fuel Rich-Forces Either Higher Turbine Temps or More Complex Tripropellant Preburner Possibly Most Weight
One for O_2/H2 One for O_2/RP	Mix of Both of the Above	

- **Baseline**
  - **Make No Specific Attempt to Minimize Number of Preburners**

- **Argument Does Not Apply to GGs**

TA3–0763

Tripropellant Comparison Study
Cooling Circuits

- Potential Options
  - H_2, RP, O_2 in Any Combination

- However
  - H_2 is the Most Efficient Coolant and Will Always be Used for Some of the Cooling
  - Each Fluid Used as a Coolant Must be Pumped to a Higher Pressure
  - Fuel and Oxidizer Coolants Used Together Pose Potential Operability Problems

- Consequently
  - Baseline H_2 as Only Coolant Used
    - Use Additional Coolants If, and Only If, Advantageous

TA3–0741

Alternate Propulsion Subsystem Concepts
Tripropellant Configuration Study
Combined Mode 1/Mode 2 Oxygen Pump

- Single Chamber
  - Weight Impact
    - Single Versus Two Pumps — +35 lbm
    - Extra Manifolding — 0 lbm
    - Hot Gas Valve — 0 lbm
  - Some Constraints on Pump Operating Map
    - Mode 2 Head — -52%
    - Mode 2 Flow — -56%

- Bell Annular
  - Weight Impact
    - Single Versus Two Pumps — +35 lbm
    - Extra Manifolding — +11 lbm
    - Hot Gas Valve — +177 lbm
  - Major Constraints on Pump Operating Map
    - Mode 2 Head — ~ Equal
    - Mode 2 Flow — -72%

- Conclusions
  - Single Chamber
    - Use Combined Mode 1/Mode 2 Oxygen Pump Whenever Possible
  - Bell Annular
    - Do Not Use Combined Mode 1/Mode 2 Oxygen Pump at All

TA3-0865

Tripropellant Comparison Study

Resulting Baseline Cycle Groundrules

- Closed Cycles Limited to FFSCC, SCC, and Hybrid Cycle Variants
  - Hybrid Cycle Limited to H_2 Driven RP Pump

- No RP in Mode 2

- H_2 Used as Primary Coolant

- Preburners
  - No Attempt to Minimize Number of Preburners
    - One Preburner per Turbine May be Ideal
  - Use H_2 for Ox Rich Preburners Where Available
  - For Fuel Rich Preburners
    - Use H_2, Then RP, Then Tripropellant

TA3–0743c

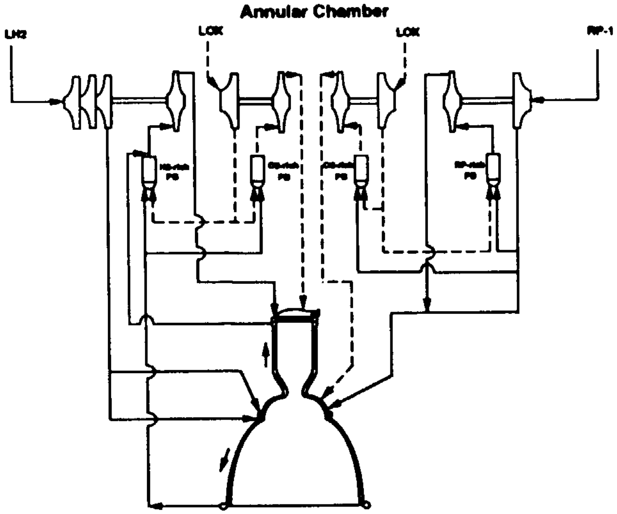
Tripropellant Comparison Study
Cycle Classes Included

- FFSCC (cf. RS-2000)
- Fuel Rich SCC (cf. RD-0120TP)
- Ox Rich SCC (cf. RD-704)
- Hybrid Cycle
  - Limited - H_2 Driven RP Pump
- GG
  - Bipropellant Only
- Within Each Cycle Class
  - Many Turbomachinery and Preburner Options

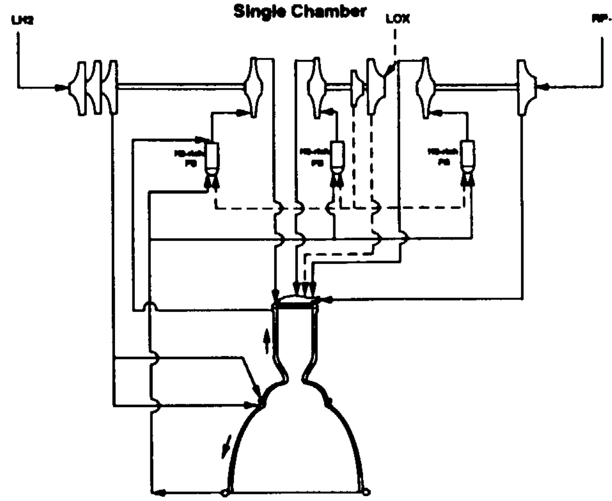
TA3–0744a

Tripropellant Comparison Study
Selected Engine Cycles

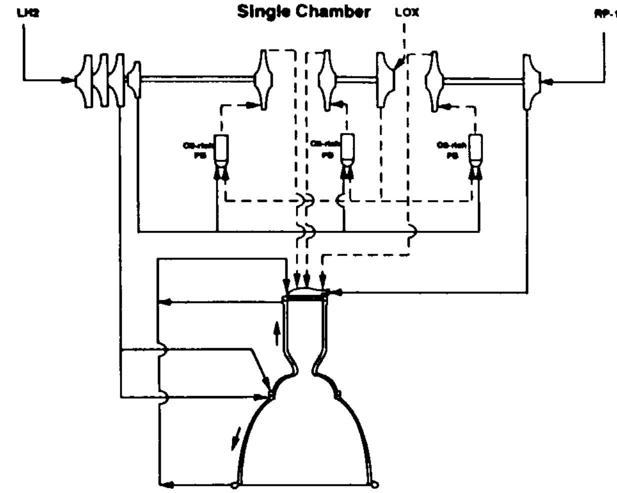
FFSCC-1(A) LOX/RP/H2 Engine Schematic
Annular Chamber



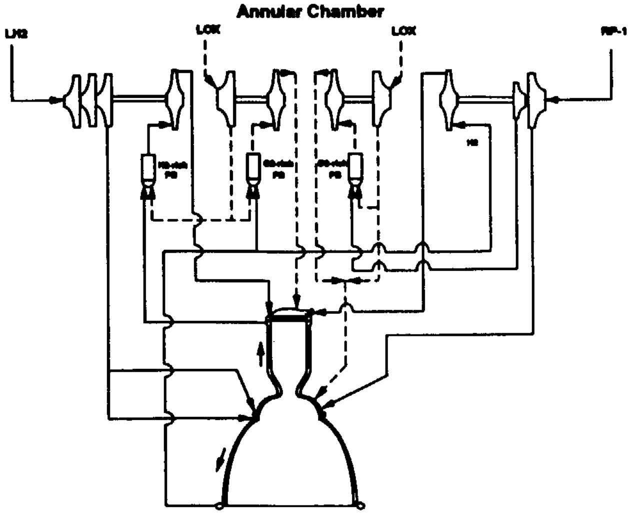
FRSCC-2(SC) LOX/RP/H2 Engine Schematic
Single Chamber



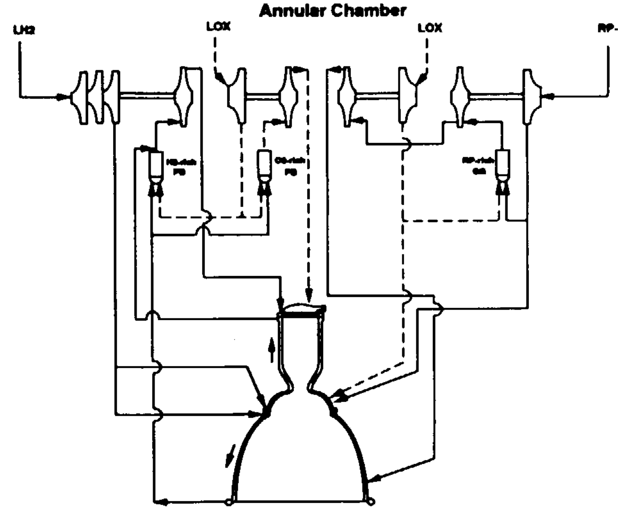
ORSCC-2(SC) LOX/RP/H2 Engine Schematic
Single Chamber



Hybrid-1(A) LOX/RP/H2 Engine Schematic
Annular Chamber



GG-3(A) LOX/RP/H2 Engine Schematic
Annular Chamber



TA3-0869

Tripropellant Comparison Study
Configuration Choices

TA3–0863a

Alternate Propulsion Subsystem Concepts
Tripropellant Configuration Study
Weight Baseline Used

- No Coatings
  - H_2 Rich
    - RIM-D1 Turbine Rotor
    - Thermo-Span Turbine Housing, Hot Gas Manifold, Preburner Body
  - RP Rich
    - Inco 718 Turbine Rotor, Housing, Hot Gas Manifold, Preburner Body
  - O2 Rich
    - Haynes 214 Turbine Rotor, Housing, Hot Gas Manifold, Preburner Body

- Welded
  - Fuel Turbopumps, Hot Gas Manifolds, Preburner Bodies
  - Coolant Manifolds
  - LOX Pump
  - Hydrogen and Oxygen Ducting

- Cast
  - Ox Rich Turbine, Hot Gas Manifold, Preburner Body
  - RP Ducts

TA3–0866

Tripropellant Comparison Study

FFSCC Cases

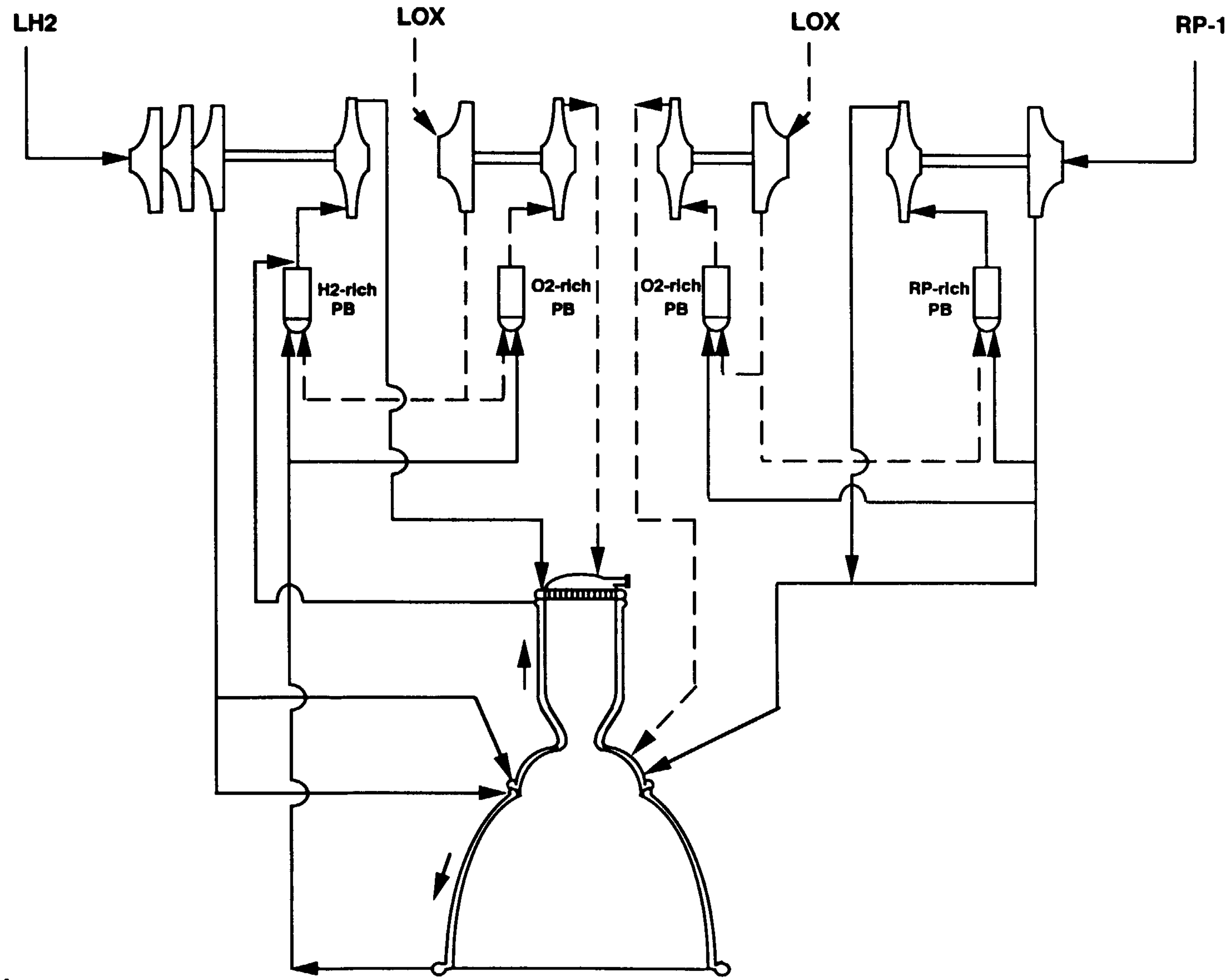
	H_2	RP	O_2 Mode 1	O_2 Mode 2	SC	Annular
FFSCC-1	H_2 Rich	RP Rich	O_2 Rich	O_2 Rich	—	√ G/G G/G
FFSCC-2	H_2 Rich	RP Rich	← O_2 Rich Combined O_2 Pump →		√ G/G/G G/G	—
FFSCC-3	H_2 Rich	← O_2 Rich Single Shaft →		O_2 Rich	√ G/L/G G/G	√ L/G G/G
FFSCC-4	H_2 Rich	← O_2 Rich Single Shaft Combined O_2 Pump →			√ G/L/G G/G	—
FFSCC-5	H_2 Rich	H_2 Rich	O_2 Rich	O_2 Rich	—	√ L/G G/G
FFSCC-6	H_2 Rich	H_2 Rich	← O_2 Rich Combined O_2 Pump →		√ G/L/G G/G	—

		MCC Injection		H_2/RP/O_2	
√	Applicable	G	Gas	X/X/X	Mode 1
—	Not Applicable	L	Liquid	X/X/X	Mode 2
SC	Single Chamber				

TA3–0746a

Tripropellant Configuration Study
FFSCC-1(A) LOX/RP/H2 Engine Schematic

Annular Chamber



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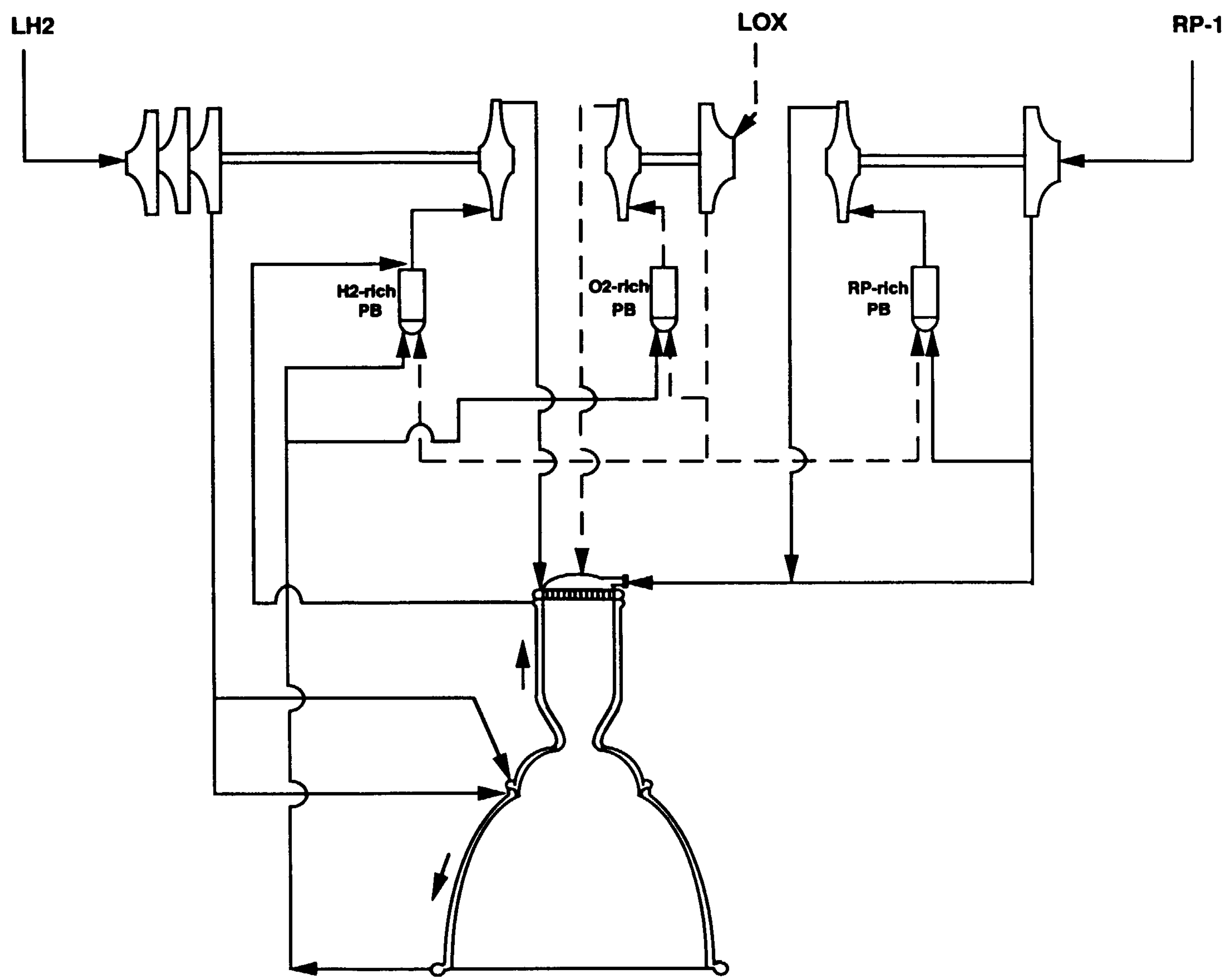
TA3-0801

Tripropellant Configuration Study
FFSCC-2(SC) LOX/RP/H2 Engine Schematic

Single Chamber



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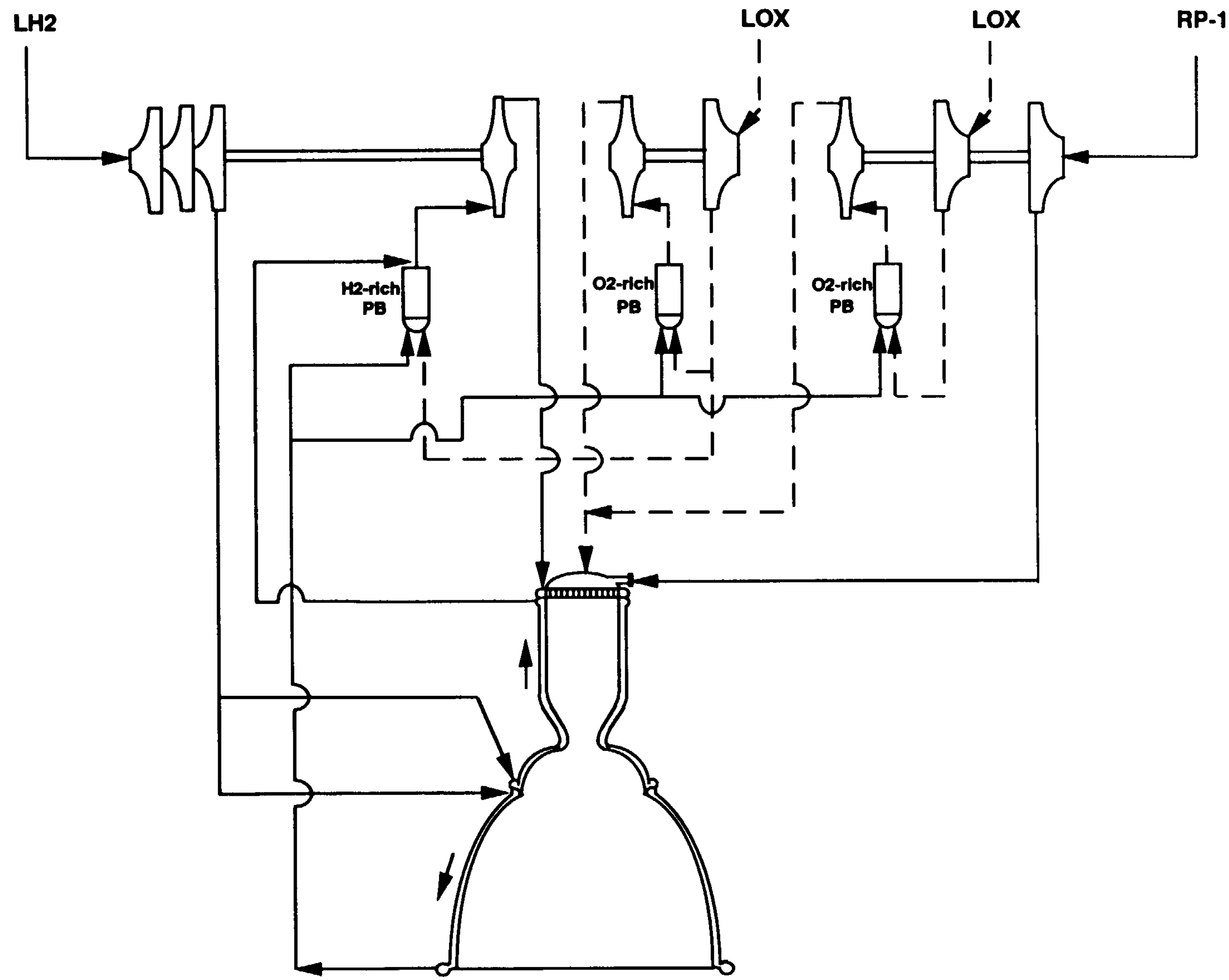
TA3-0802

Tripropellant Configuration Study
FFSCC-3(SC) LOX/RP/H2 Engine Schematic

Single Chamber

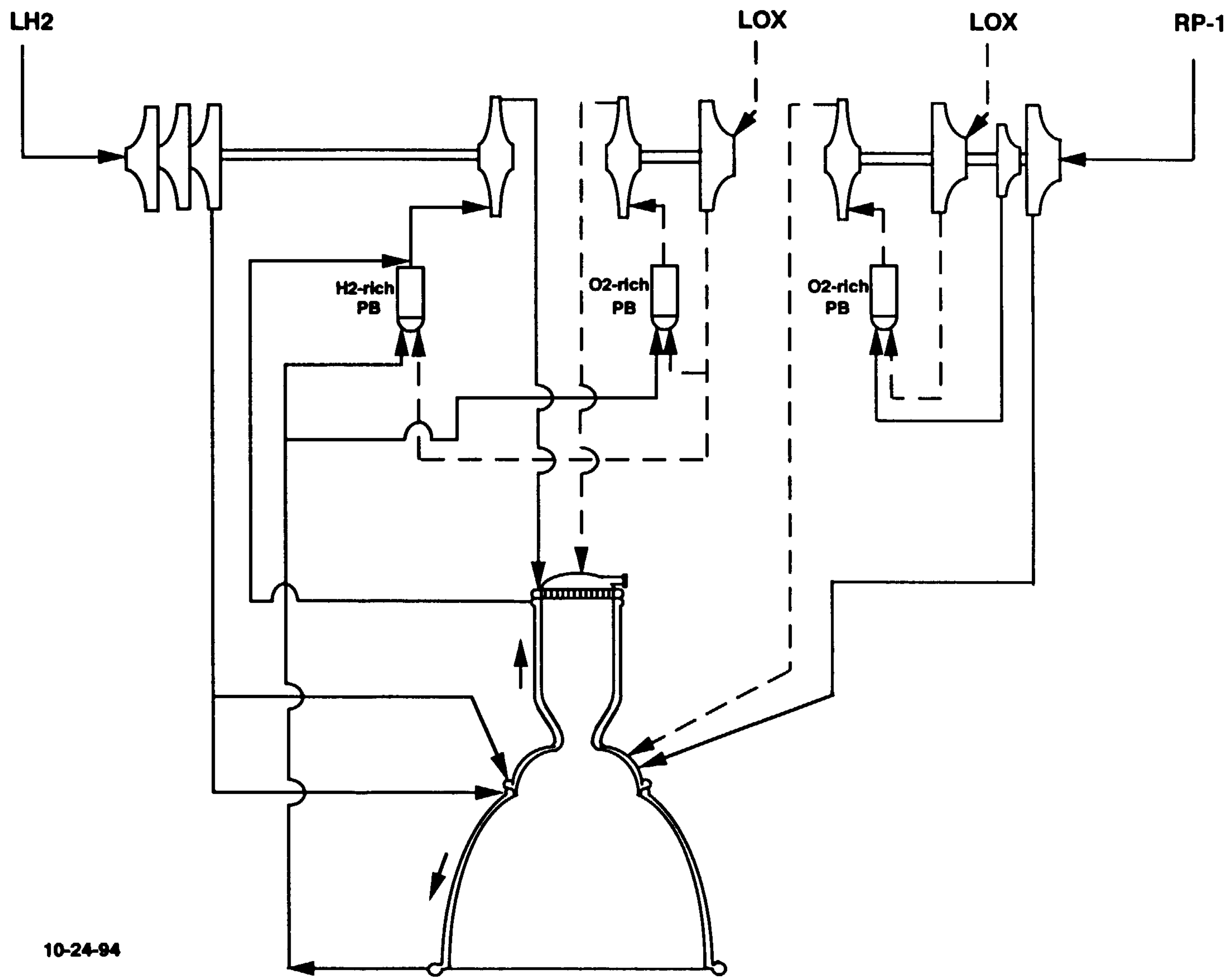


10-24-94

TA3–0804

Tripropellant Configuration Study
FFSCC-3(A) LOX/RP/H2 Engine Schematic

Annular Chamber

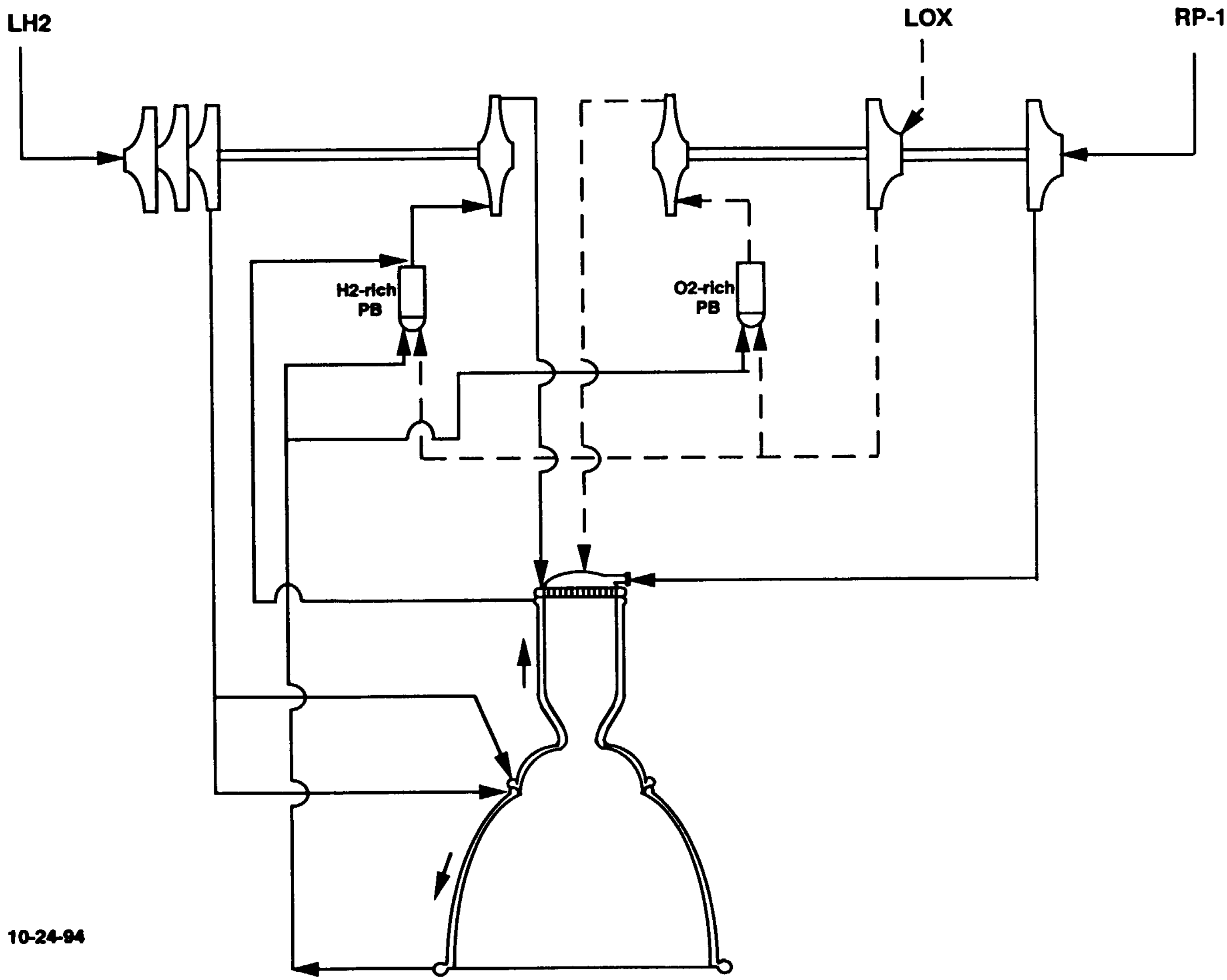


10-24-94

TA3–0805

Tripropellant Configuration Study
FFSCC-4(SC) LOX/RP/H2 Engine Schematic

Single Chamber

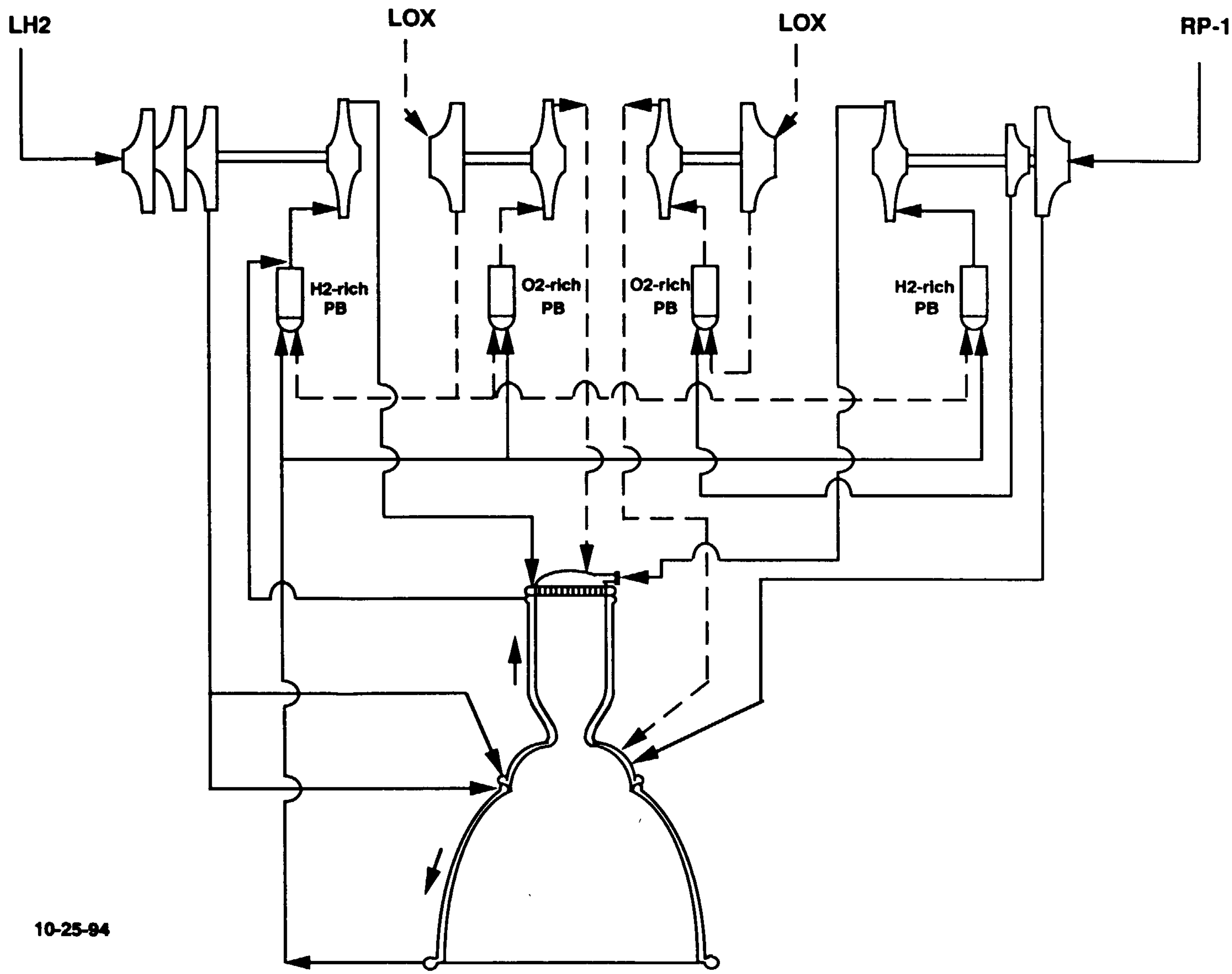


10-24-94

TA3–0806

Tripropellant Configuration Study
FFSCC-5(A) LOX/RP/H2 Engine Schematic

Annular Chamber

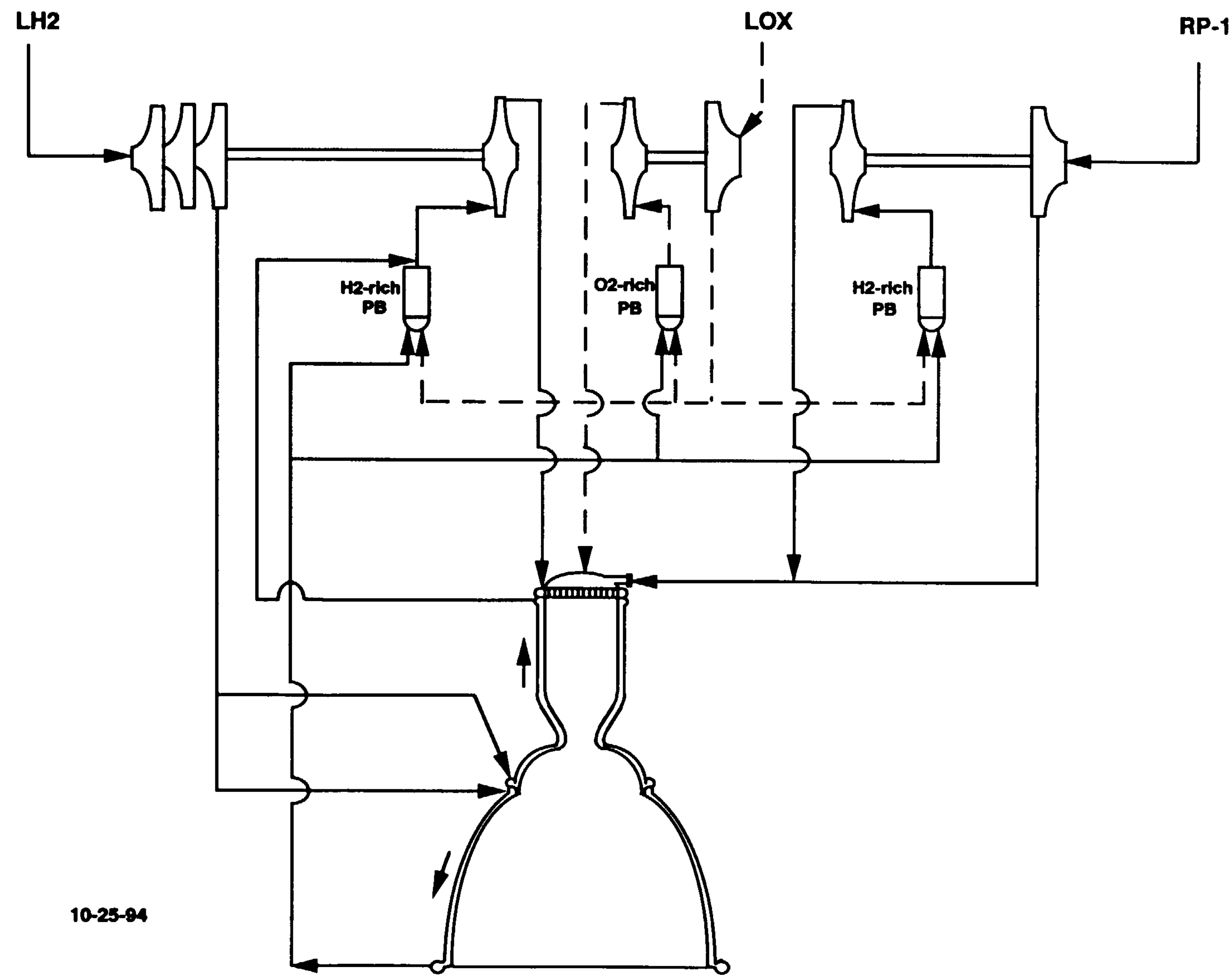


10-25-94

TA3-0808

Tripropellant Configuration Study
FFSCC-6(SC) LOX/RP/H2 Engine Schematic

Single Chamber



TA3–0809

Tripropellant Comparison Study

FFSCC Cases

	Cycle (Relative Weight) (SC/Annular)	H_2 (Tur Temp, °R)	RP (Tur Temp, °R)	O_2 Mode 1 (Tur Temp, °R)	O_2 Mode 2 (Tur Temp, °R)	SC	Annular
√	FFSCC-1 (— / 1.000)	H_2 Rich 1,100	RP Rich 1,394	O_2 Rich 1,100	O_2 Rich 1,100	—	√ G/G G/G
√	FFSCC-2 (1.000 / —)	H_2 Rich 1,100	RP Rich 1,400	← O_2 Rich Combined O_2 Pump 1,100 →		√ G/G/G G/G	—
	FFSCC-3 (1.040 / 1.050)	H_2 Rich 1,100/1,100	← O_2 Rich Single Shaft 1,100/1,185 →		O_2 Rich 1,100/1,100	√ G/L/G G/G	√ L/G G/G
	FFSCC-4 (1.061 / —)	H_2 Rich 1,100	← O_2 Rich Single Shaft Combined O_2 Pump 1,100 →			√ G/L/G G/G	—
	FFSCC-5 (— / 1.024)	H_2 Rich 1,555	H_2 Rich 1,100	O_2 Rich 1,100	O_2 Rich 1,100	—	√ L/G G/G
	FFSCC-6 (1.010 / —)	H_2 Rich 1,172	H_2 Rich 1,100	← O_2 Rich Combined O_2 Pump 1,100 →		√ G/L/G G/G	—

√	Applicable	MCC Injection		H_2/RP/O_2	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3-0746e

Alternate Propulsion Subsystem Concepts
FFSCC Cases

- Baseline Turbomachinery/Preburner Arrangement Selection
  - Single Chamber
    - FFSCC-2
      - Lightest Weight
      - Only Single Chamber System With No Vehicle He Flow
  - Bell Annular
    - FFSCC-1
      - Lightest Weight
      - Only Bell Annular System With No Vehicle He Flow

TA3–0875

Tripropellant Comparison Study
Ox Rich SCC Cases

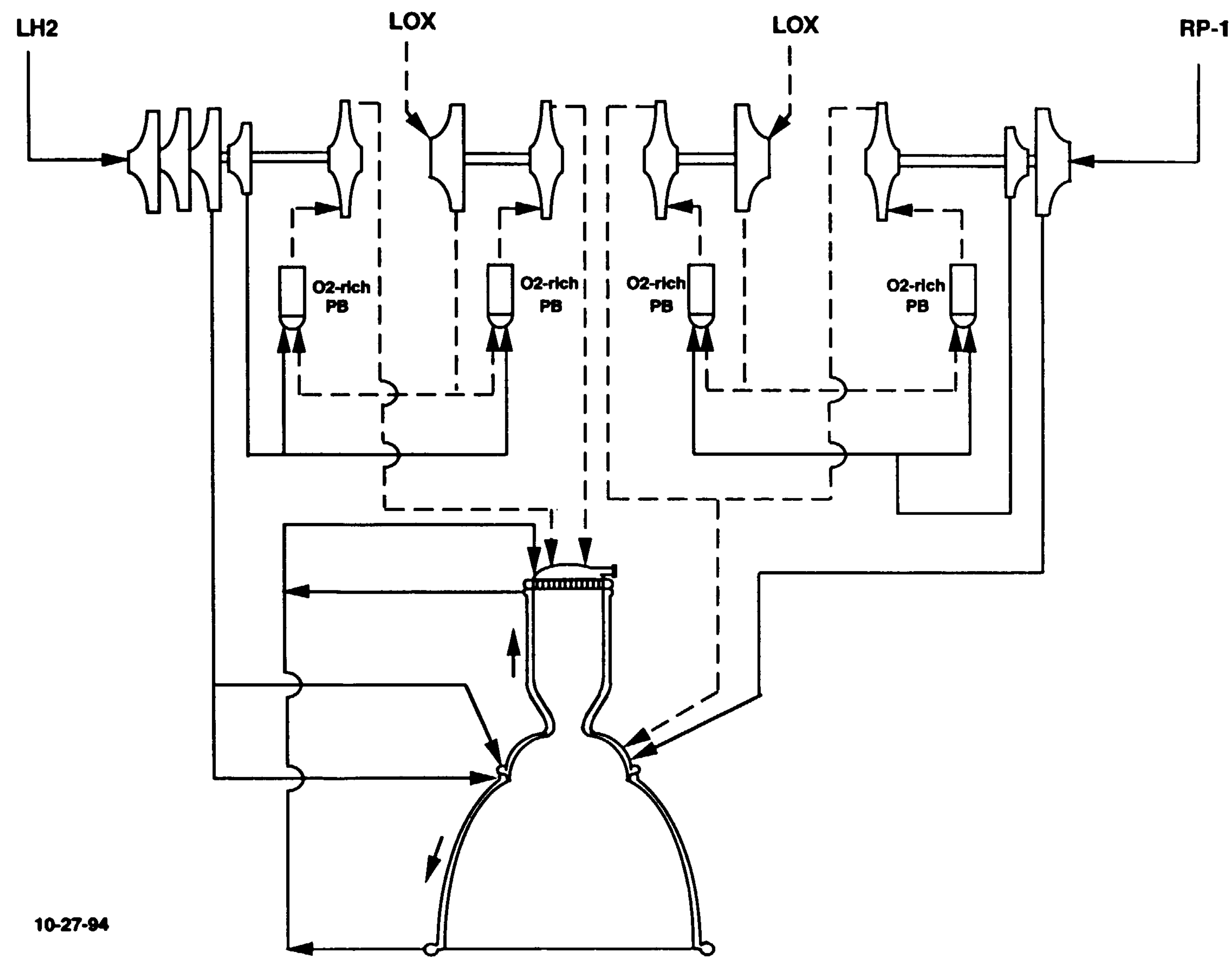
	H_2	RP	O_2 Mode 1	O_2 Mode 2	SC	Annular
ORSCC-1	O_2 Rich	O_2 Rich	O_2 Rich	O_2 Rich	—	√ L/G G/G
ORSCC-2	O_2 Rich	O_2 Rich	← O_2 Rich Combined O_2 Pump	→	√ G/L/G G/G	—
ORSCC-3	O_2 Rich	← O_2 Rich Single Shaft	→	O_2 Rich	—	√ L/G G/G
ORSCC-4	O_2 Rich	← O_2 Rich Single Shaft Combined O_2 Pump		→	√ G/L/G G/G	—

√	Applicable	MCC Injection		$H_2/RP/O_2$	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3–0749a

Tripropellant Configuration Study
ORSCC-1(A) LOX/RP/H2 Engine Schematic

Annular Chamber

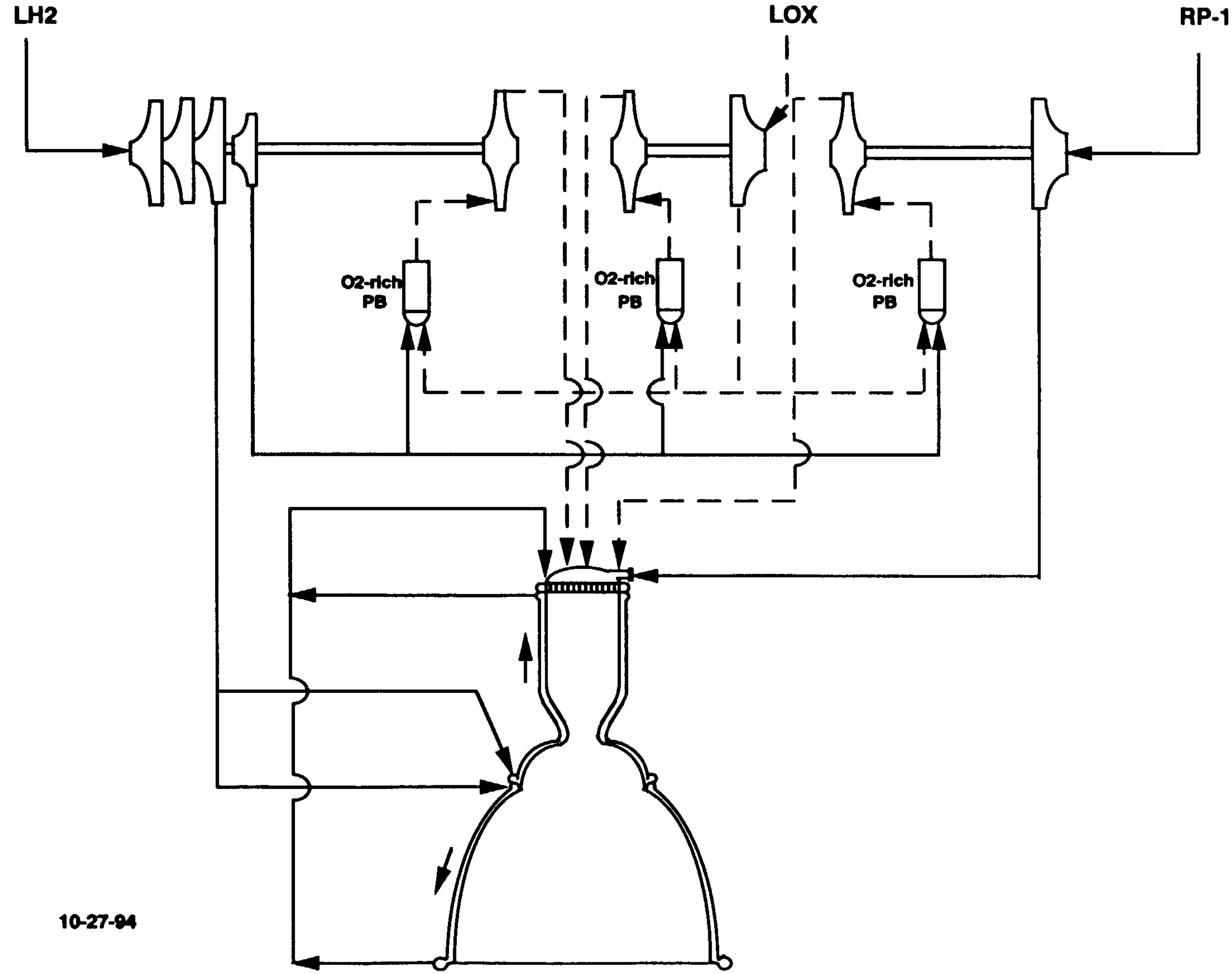


10-27-94

TA3–0822

Tripropellant Configuration Study
ORSCC-2(SC) LOX/RP/H2 Engine Schematic

Single Chamber

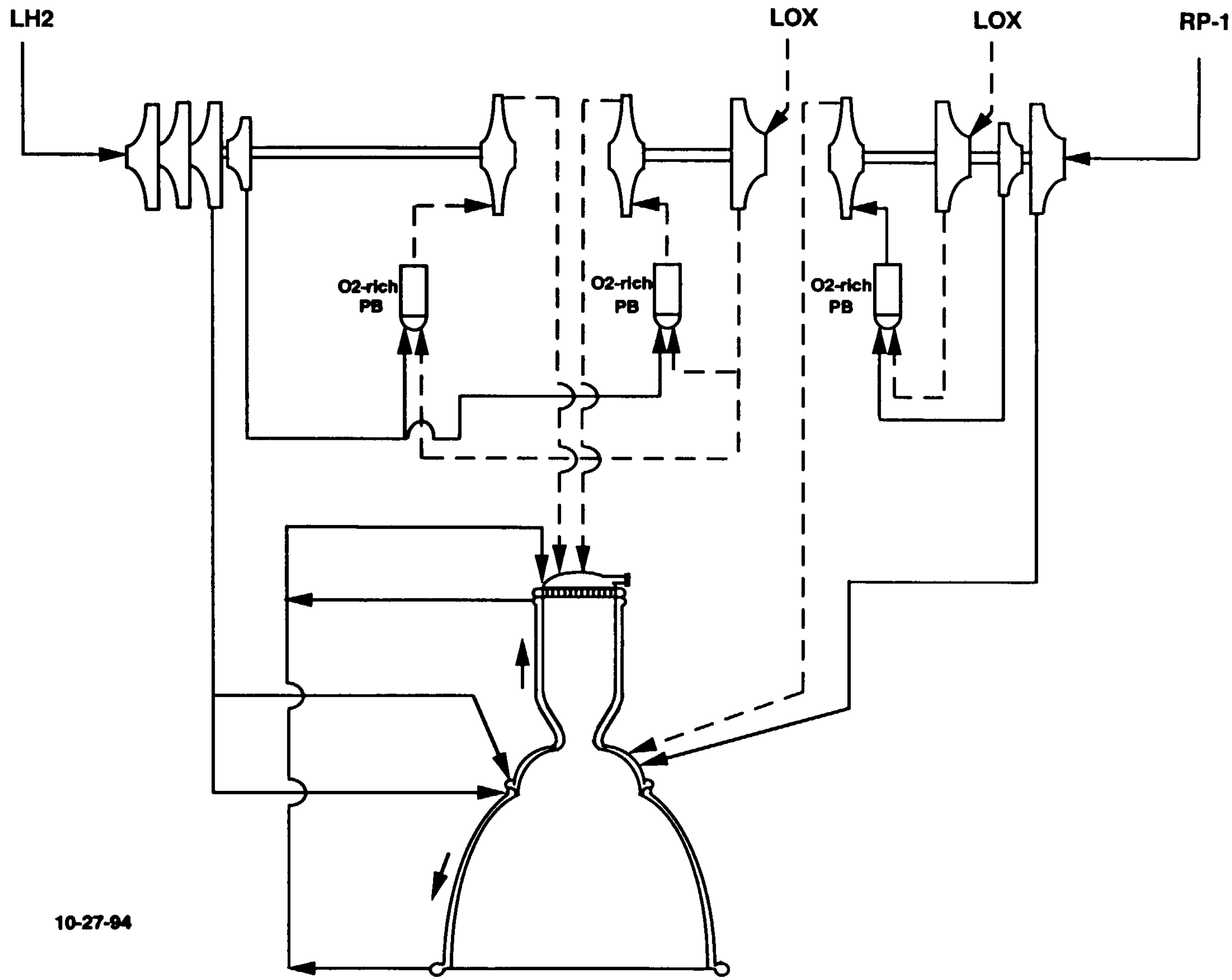


10-27-94

TA3–0823

Tripropellant Configuration Study
ORSCC-3(A) LOX/RP/H2 Engine Schematic

Annular Chamber

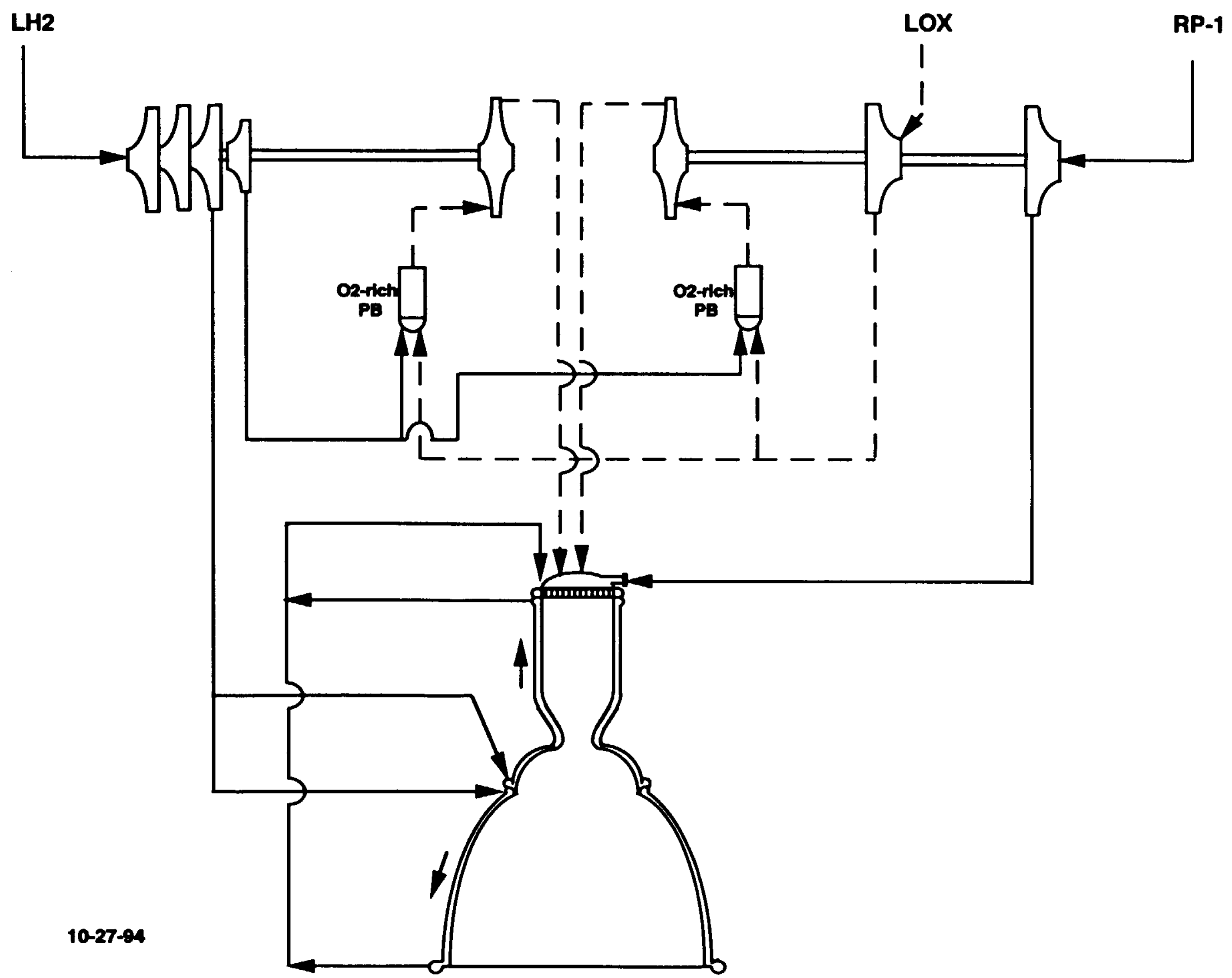


10-27-94

TA3–0824

Tripropellant Configuration Study
ORSCC-4(SC) LOX/RP/H2 Engine Schematic

Single Chamber



10-27-94

TA3–0825

Tripropellant Comparison Study

Ox Rich SCC Cases

Cycle (Relative Weight) (SC/Annular)	H_2 (Tur Temp, °R)	O_2 RP (Tur Temp, °R)	O_2 Mode 1 (Tur Temp, °R)	O_2 Mode 2 (Tur Temp, °R)	SC	Annular
ORSCC-1 (— / *)	O_2 Rich	O_2 Rich	O_2 Rich	O_2 Rich	—	√ L/G G/G
√ ORSCC-2 (1.000 / —)	O_2 Rich 1,633	O_2 Rich 1,511	← O_2 Rich Combined O_2 Pump 1,519	→	√ G/L/G G/G	—
ORSCC-3 (— / *)	O_2 Rich	← O_2 Rich Single Shaft	→	O_2 Rich	—	√ L/G G/G
ORSCC-4 (1.054 / —)	O_2 Rich 1,616	← O_2 Rich Single Shaft Combined O_2 Pump 1,612		→	√ G/L/G G/G	—

* Turbine Tenperatures Excessive
Pri Ox – 2,284°R
Pri Fuel – 2,287°R

√ Applicable
— Not Applicable
SC Single Chamber

MCC Injection
G Gas
L Liquid

H_2/RP/O_2
X/X/X Mode 1
X/X/X Mode 2

TA3–0749c

Alternate Propulsion Subsystem Concepts
ORSCC Cases

- **Baseline Turbomachinery/Preburner Arrangement Selection**
- **H_2 Pump's Turbine is Coated**
  - **Haynes 214 AN^2 Capability Much Too Low at Temperature Needed**
  - **Single Chamber**
    - **ORSCC-2**
      - **Lightest Weight**
      - **Other Option Also Has He Usage**
  - **Bell Annular**
    - **No Viable Configuration for Ox-Rich Cycle**
      - **Primary Ox and Fuel Turbine Temperatures Too High**
        - **~2,280°R**
        - **No Way to Use Secondary Ox for Primary Power Requirements**

TA3–0891

Tripropellant Comparison Study
Fuel Rich SCC Cases

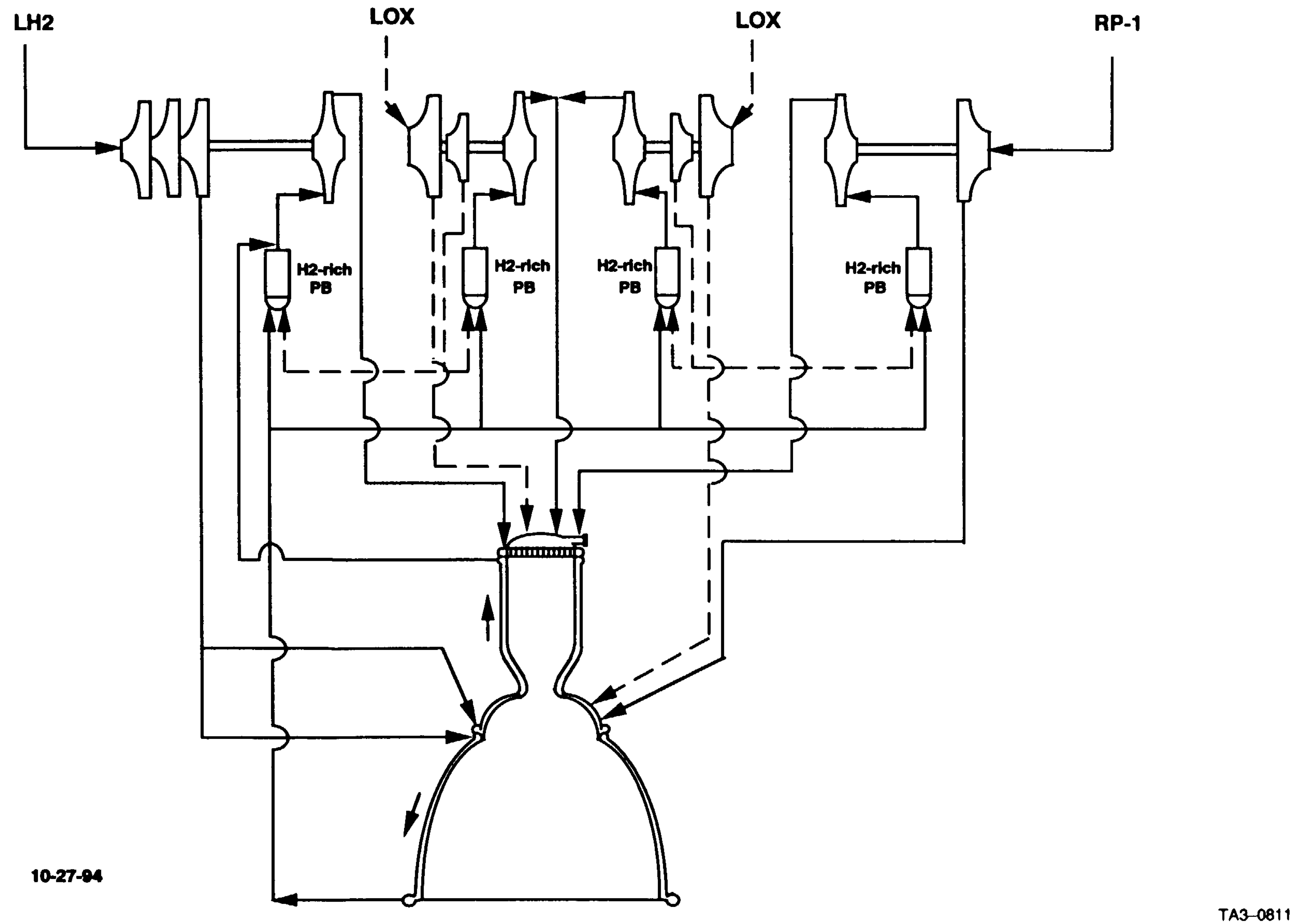
	H_2	RP	O_2 Mode 1	O_2 Mode 2	SC	Annular
FRSCC-1	H_2 Rich	H_2 Rich	H_2 Rich	H_2 Rich	—	√ L/L G/L
FRSCC-2	H_2 Rich	H_2 Rich	← H_2 Rich Combined O_2 Pump →		√ G/L/L G/L	√ L/L G/L
FRSCC-3	H_2 Rich	← H_2 Rich Single Shaft →		H_2 Rich	√ G/L/L G/L	√ L/L G/L
FRSCC-4	H_2 Rich	← H_2 Rich Single Shaft Combined O_2 Pump →			√ G/L/L G/L	√ L/L G/L
FRSCC-5	H_2 Rich	RP Rich	RP Rich	H_2 Rich	√ G/G/L G/L	√ G/L G/L
FRSCC-6	H_2 Rich	← RP Rich Combined O_2 Pump →		H_2 Rich	√ G/G/L G/L	√ G/L G/L
FRSCC-7	Tripropellant	Tripropellant	← Tripropellant Combined O_2 Pump →		√ G/G/L G/L	—

√	Applicable	MCC Injection		$H_2/RP/O_2$	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3-0752a

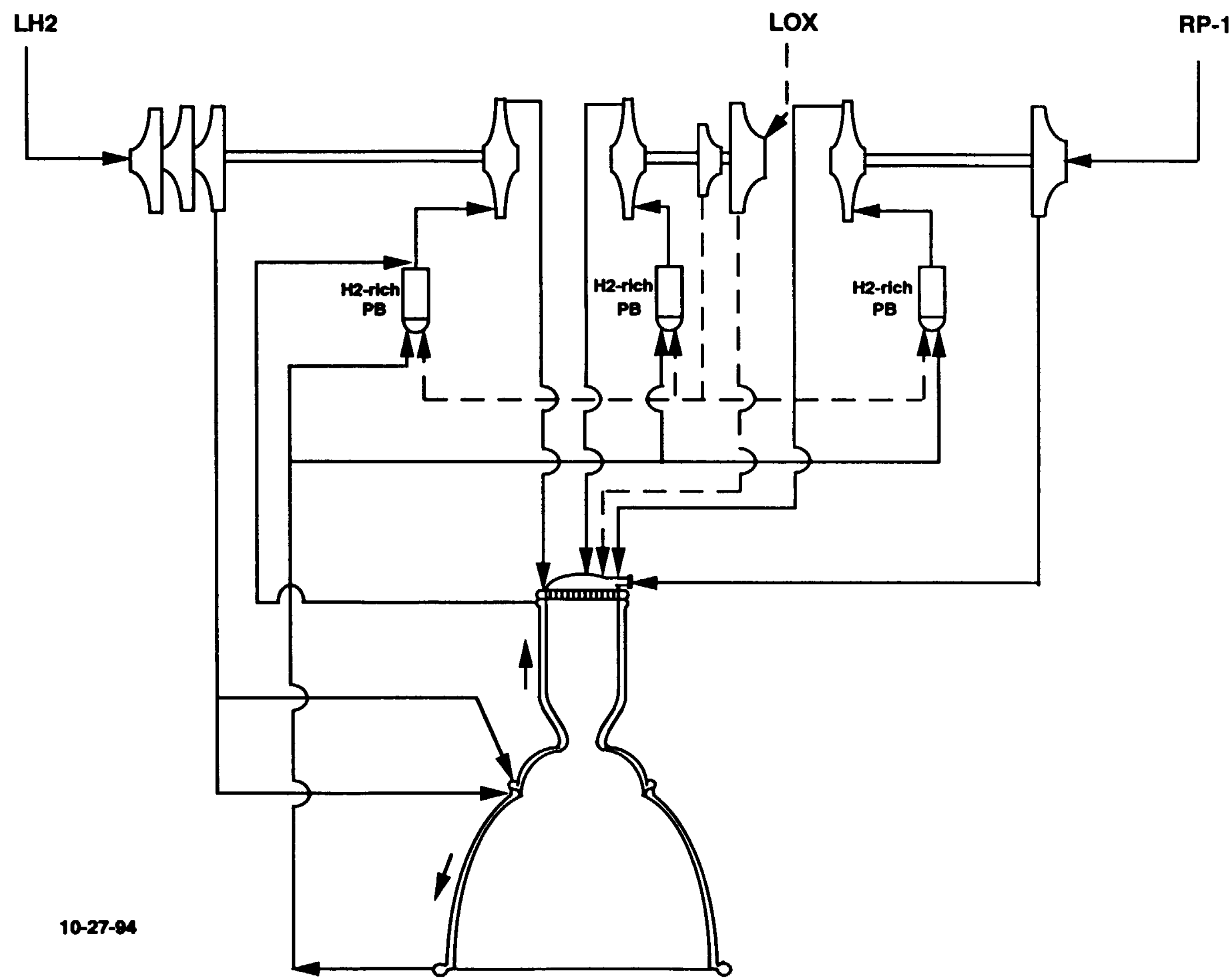
Tripropellant Configuration Study
FRSCC-1(A) LOX/RP/H2 Engine Schematic

Annular Chamber



Tripropellant Configuration Study
FRSCC-2(SC) LOX/RP/H2 Engine Schematic

Single Chamber

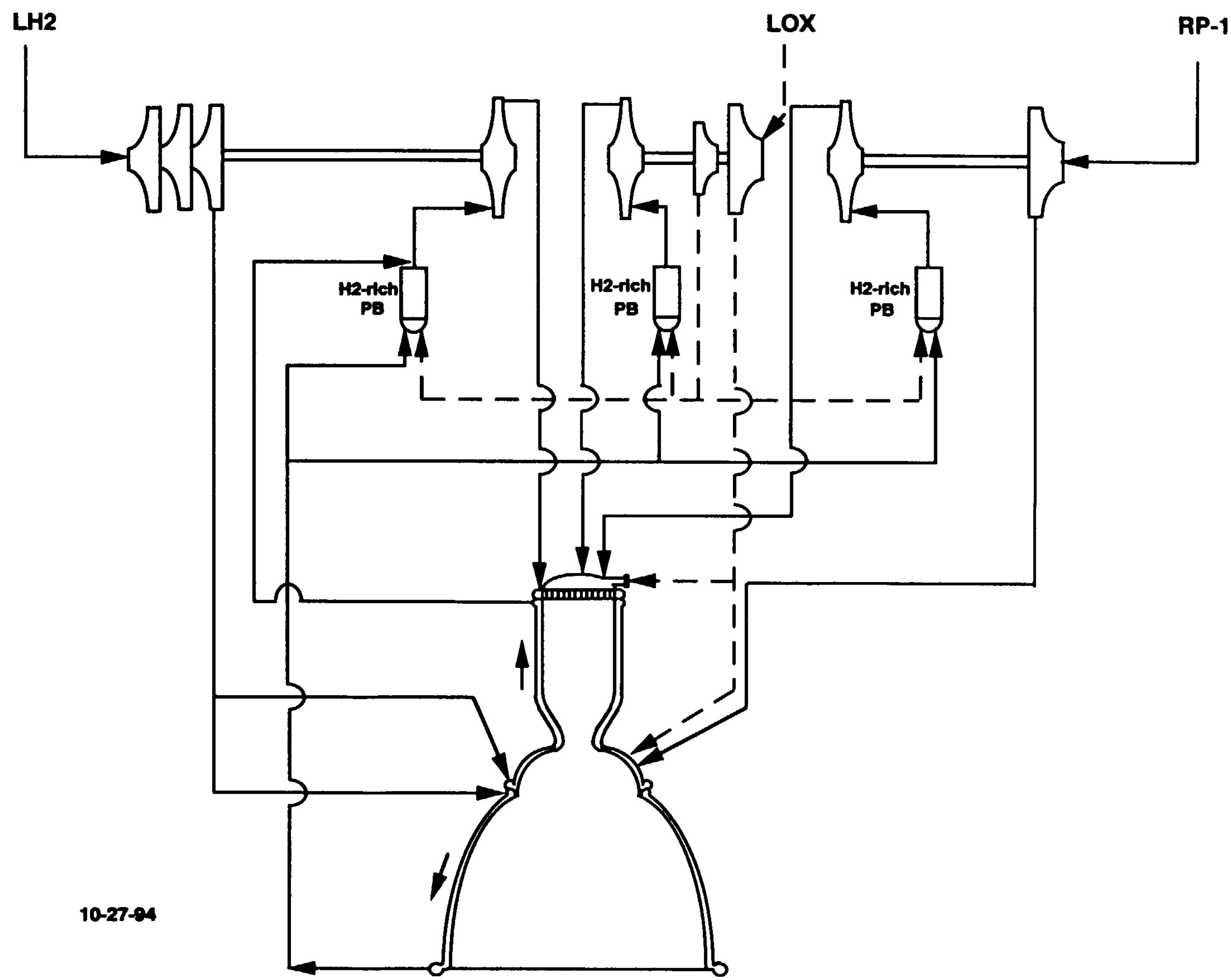


10-27-94

TA3–0812

Tripropellant Configuration Study
FRSCC-2(A) LOX/RP/H2 Engine Schematic

Annular Chamber

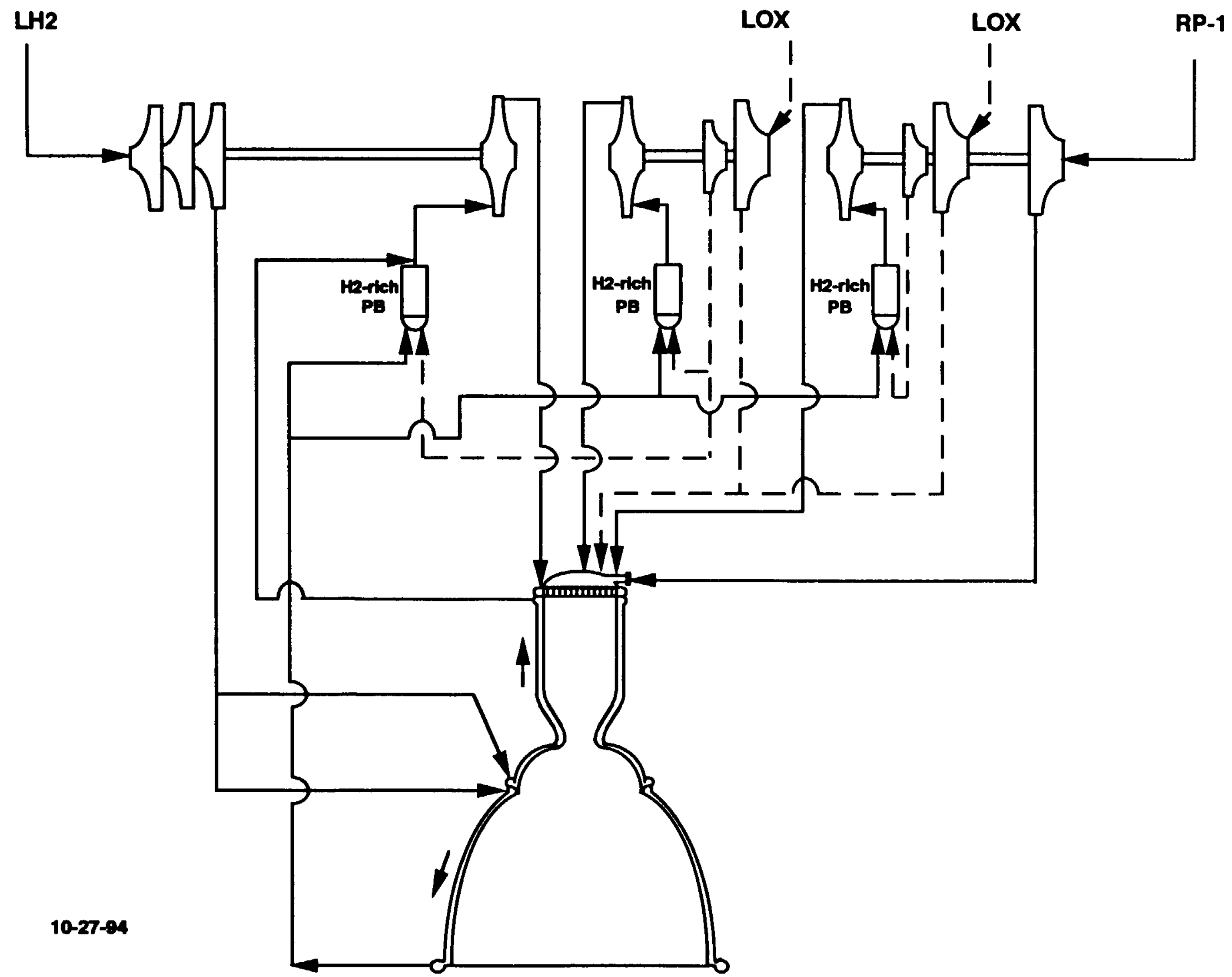


10-27-94

TA3-0813

Tripropellant Configuration Study
FRSCC-3(SC) LOX/RP/H2 Engine Schematic

Single Chamber

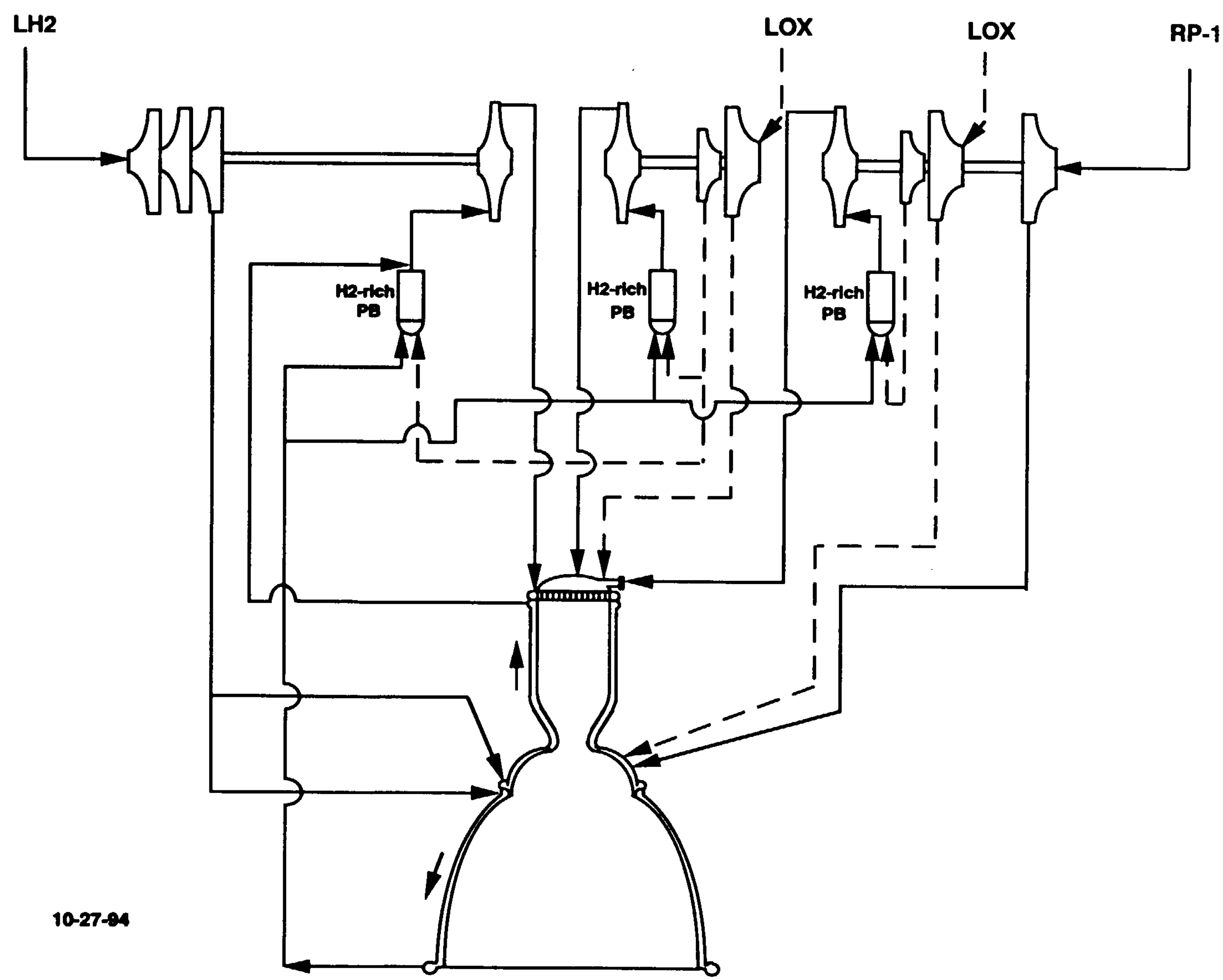


10-27-94

TA3-0814

Tripropellant Configuration Study
FRSCC-3(A) LOX/RP/H2 Engine Schematic

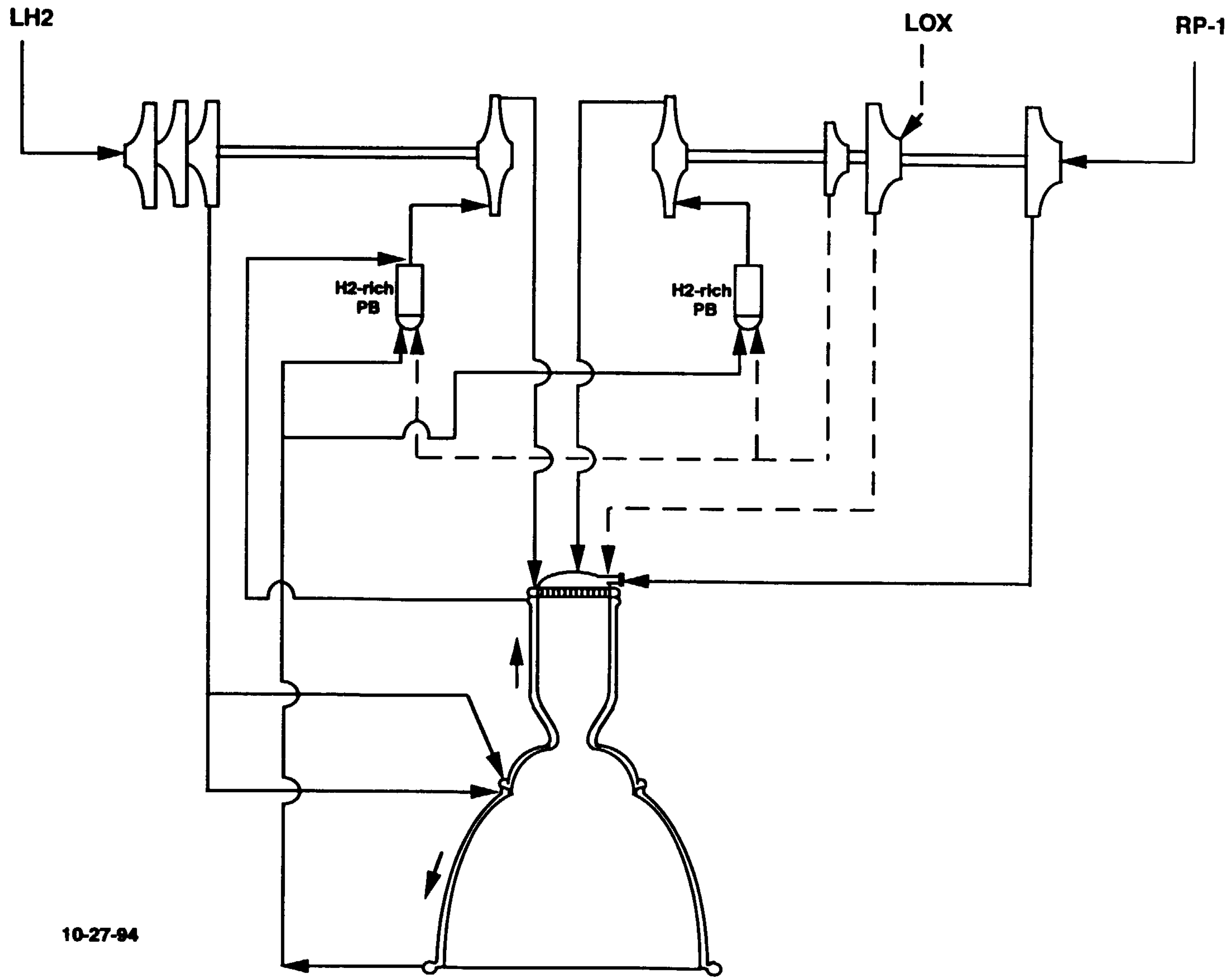
Annular Chamber



TA3–0815

Tripropellant Configuration Study
FRSCC-4(SC) LOX/RP/H2 Engine Schematic

Single Chamber

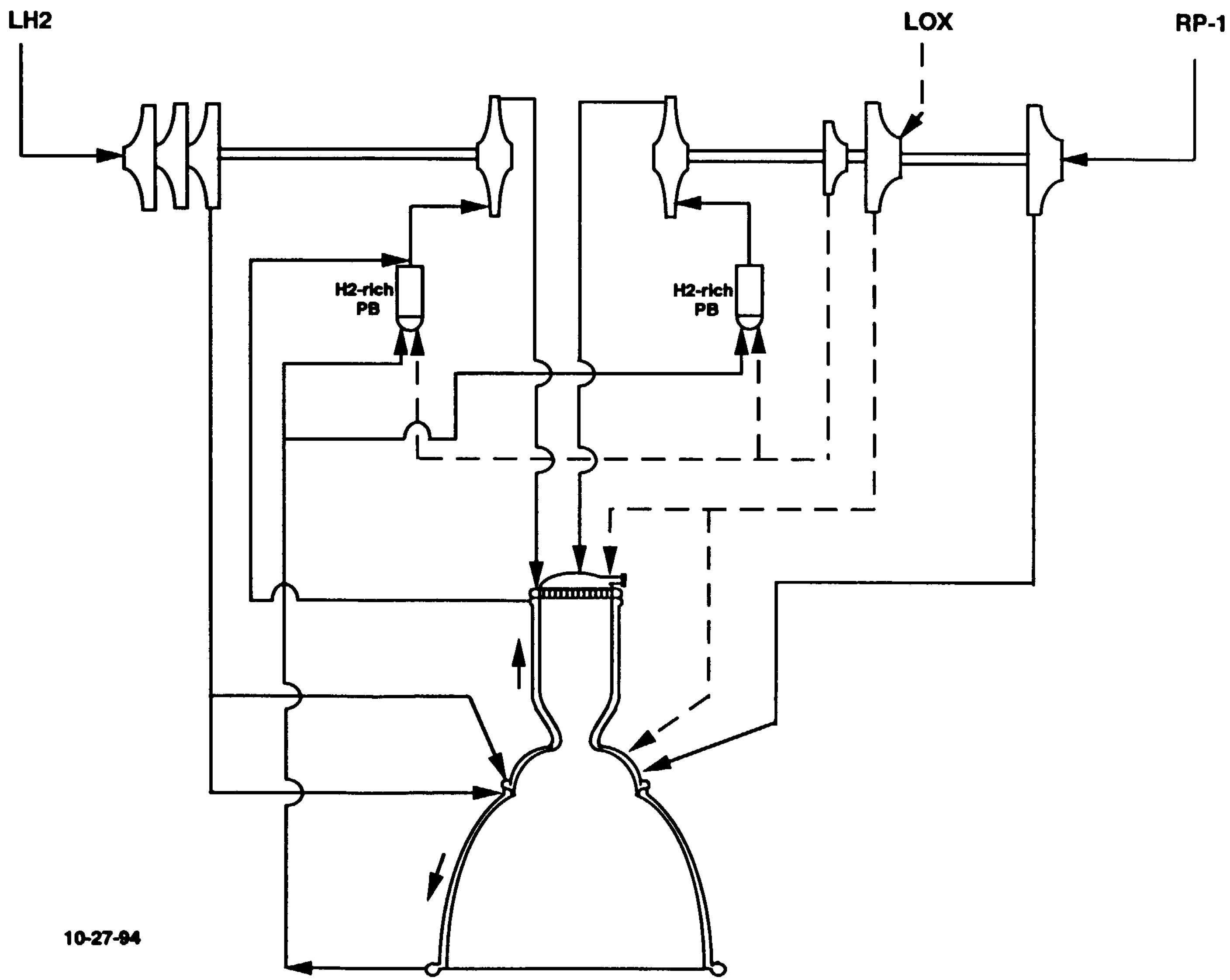


10-27-94

TA3-0816

Tripropellant Configuration Study
FRSCC-4(A) LOX/RP/H2 Engine Schematic

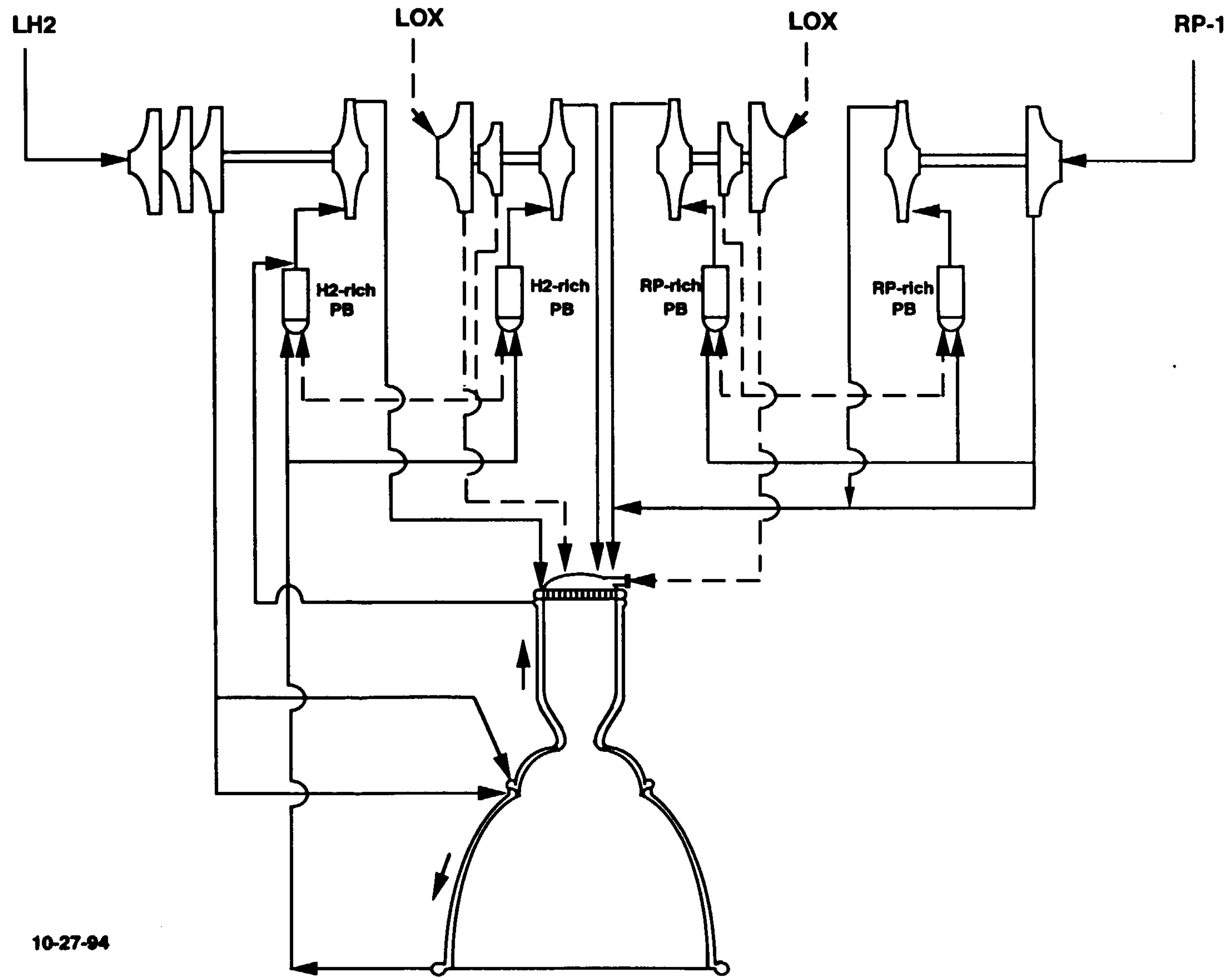
Annular Chamber



TA3–0817

Tripropellant Configuration Study
FRSCC-5(SC) LOX/RP/H2 Engine Schematic

Single Chamber

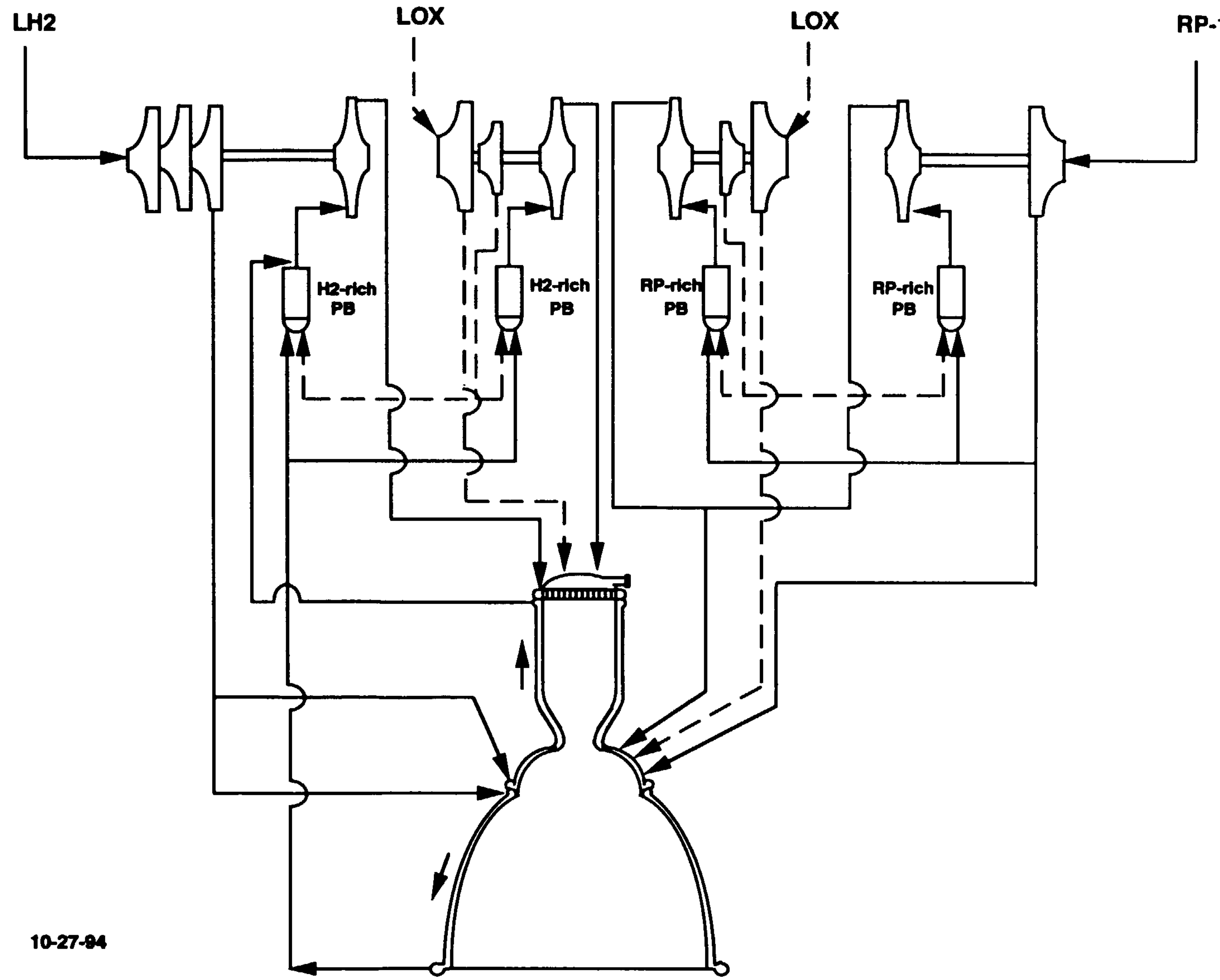


10-27-94

TA3–0818

Tripropellant Configuration Study
FRSCC-5(A) LOX/RP/H2 Engine Schematic

Annular Chamber

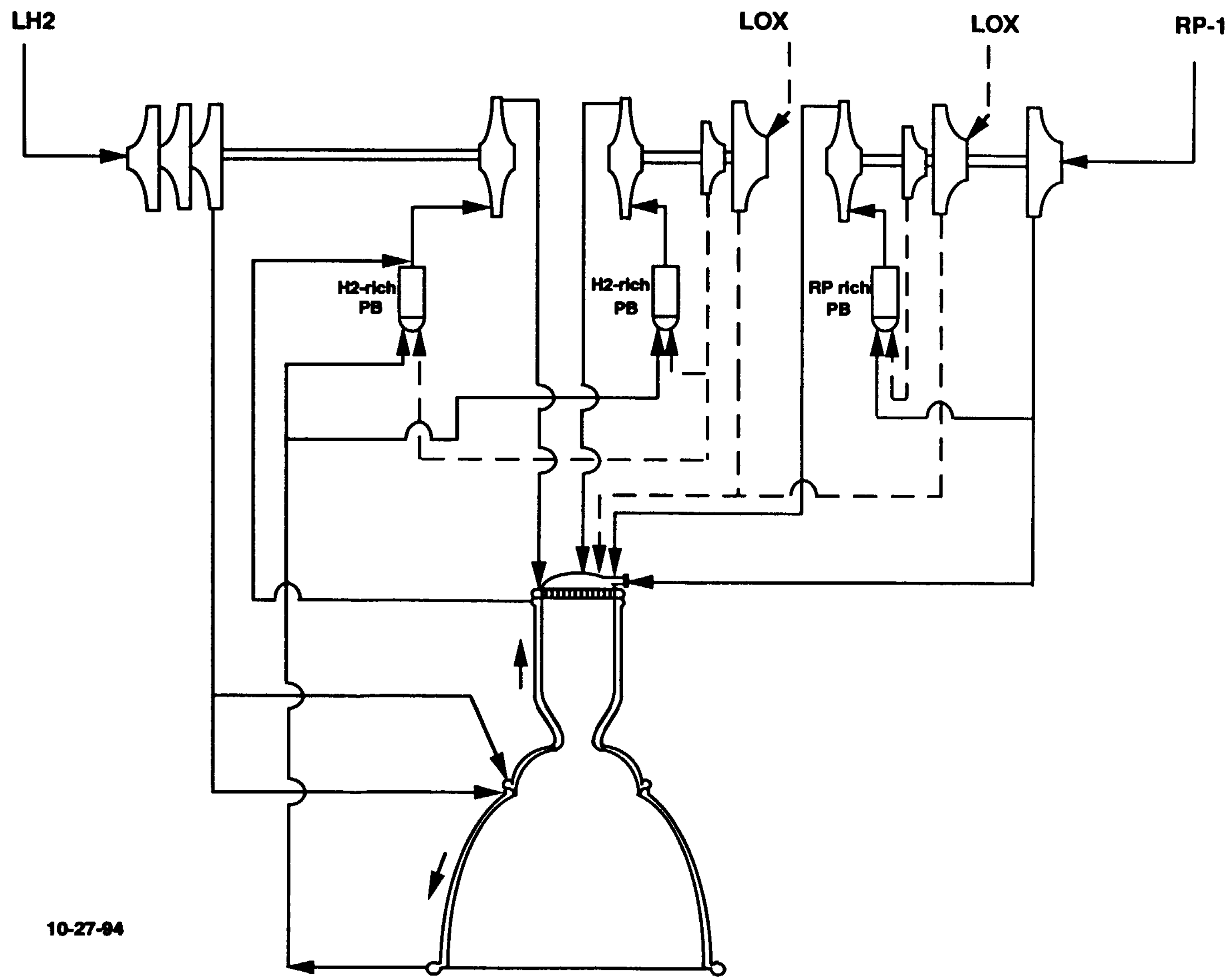


10-27-94

TA3-0819

Tripropellant Configuration Study
FRSCC-6(SC) LOX/RP/H2 Engine Schematic

Single Chamber

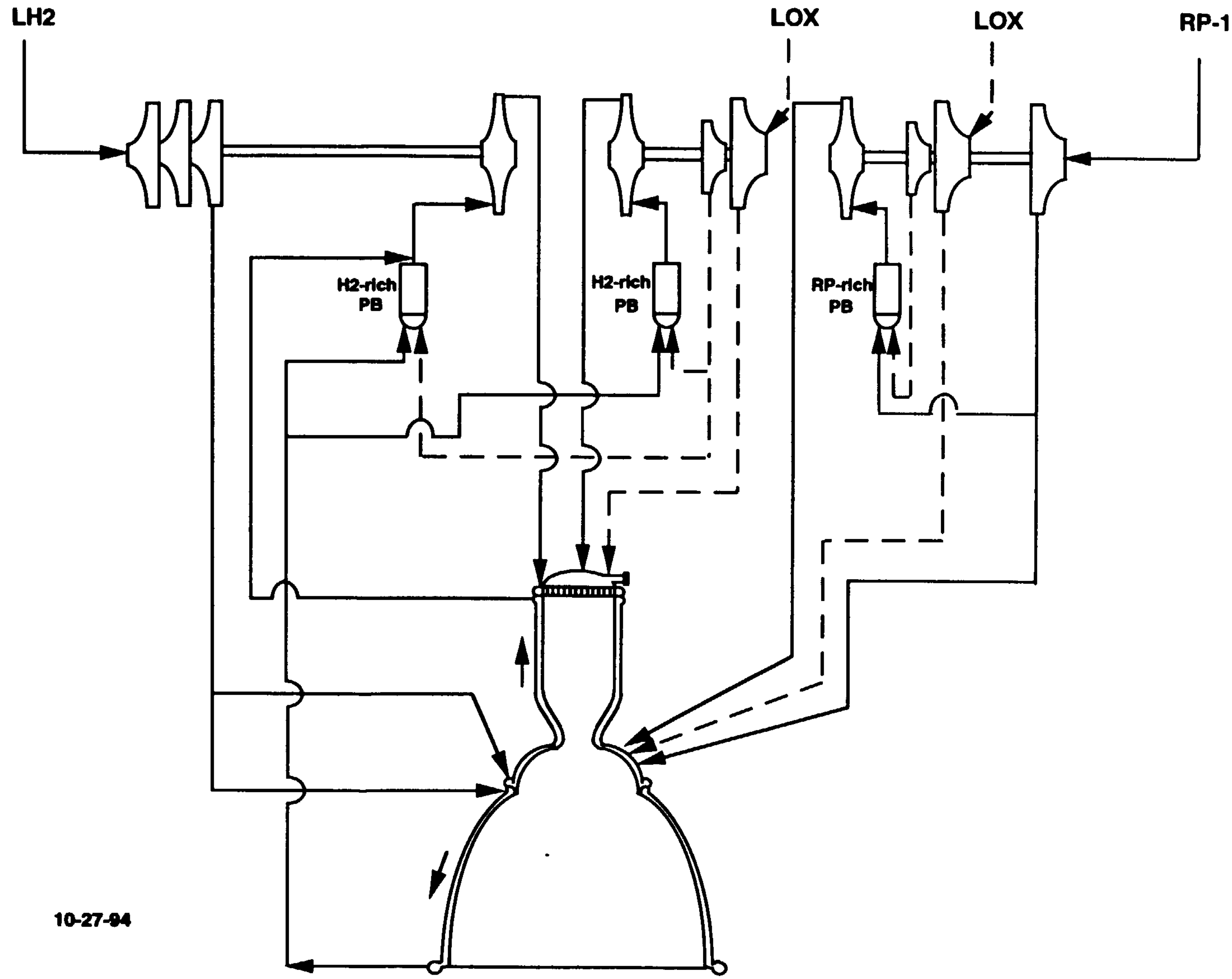


10-27-94

TA3-0820

Tripropellant Configuration Study
FRSCC-6(A) LOX/RP/H2 Engine Schematic

Annular Chamber



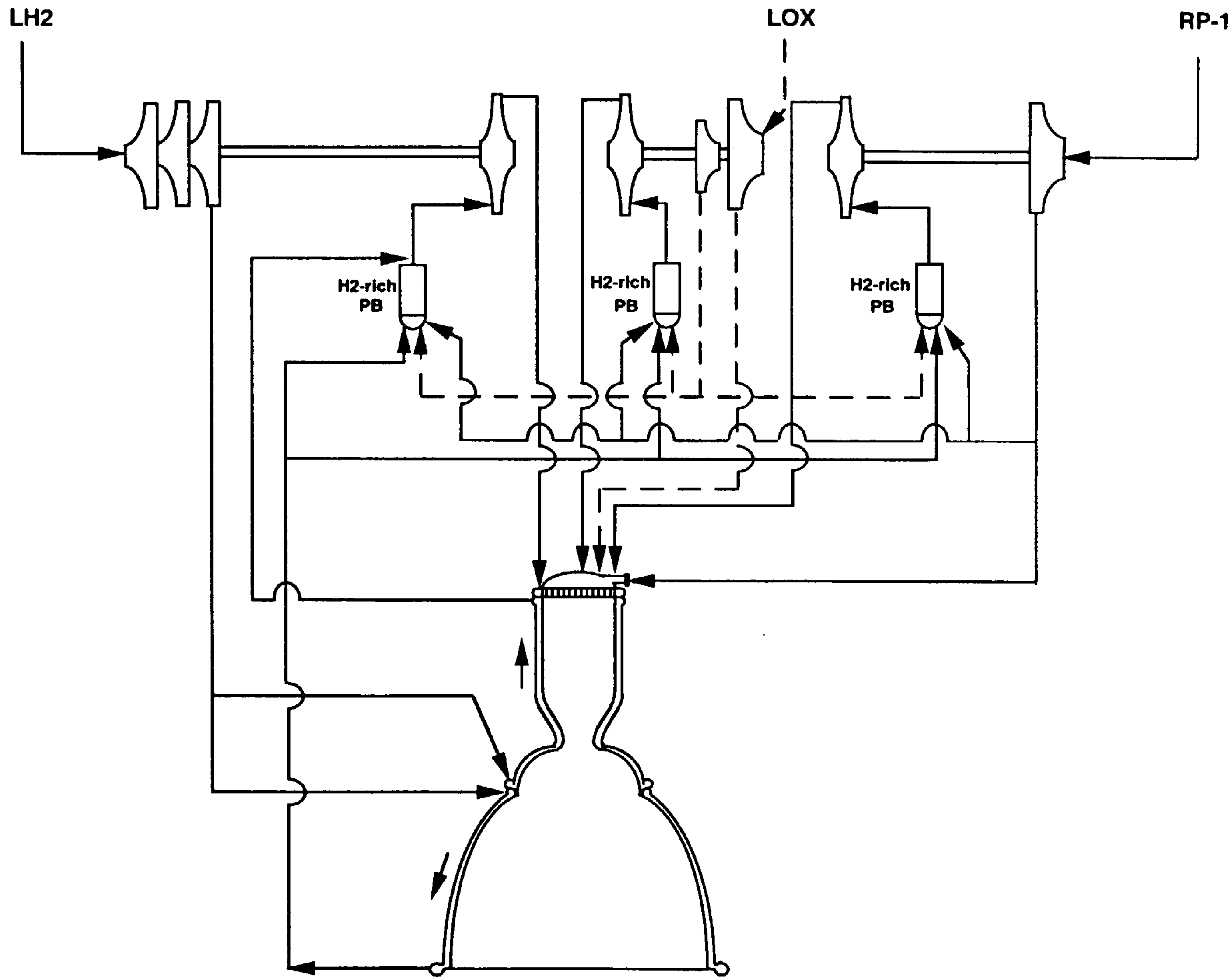
10-27-94

TA3–0821

Tripropellant Configuration Study

FRSCC-7(SC) LOX/RP/H2 Engine Schematic

Single Chamber



TA3–0812a

Tripropellant Comparison Study
Fuel Rich SCC Cases

	Cycle (Relative Weight) (SC/Annular)	H_2 (Tur Temp, °R)	RP (Tur Temp, °R)	O_2 Mode 1 (Tur Temp, °R)	O_2 Mode 2 (Tur Temp, °R)	SC	Annular
	FRSCC-1 (—/*)	H_2 Rich 1,825	H_2 Rich 1,550	H_2 Rich 1,750	H_2 Rich 1,760	—	√ L/L G/L
	FRSCC-2 (1.020/*)	H_2 Rich 1,804/1,852	H_2 Rich 1,447/1,450	← H_2 Rich Combined O_2 Pump 1,857/1,876 →		√ G/L/L G/L	√ L/L G/L
	FRSCC-3 (1.040/*)	H_2 Rich 1,800/1,848	← H_2 Rich Single Shaft 1,850/1,860 →		H_2 Rich 1,800/1,835	√ G/L/L G/L	√ L/L G/L
	FRSCC-4 (1.000/*)	H_2 Rich 1,827/1,840	← H_2 Rich Single Shaft Combined O_2 Pump 1,860/1,850 →			√ G/L/L G/L	√ L/L G/L
	FRSCC-5 (1.101/1.007)	H_2 Rich 1,453/1,447	RP Rich 1,852/1,693	RP Rich 1,897/1,897	H_2 Rich 1,120/1,748	√ G/G/L G/L	√ G/L G/L
√ (BA)	FRSCC-6 (1.103/1.000)	H_2 Rich 1,453/1,600	← RP Rich Single Shaft 1,899/1,900 →		H_2 Rich 1,127/1,400	√ G/G/L G/L	√ G/L G/L
√	FRSCC-7 (1.029/—)	Tripropellant 1,700	Tripropellant 1,700	← Tripropellant Combined O_2 Pump 1,700 →		√ G/G/L G/L	—

* Excessive turbine temperature due to thrust split

√ Applicable
— Not Applicable
SC Single Chamber

MCC Injection
G Gas
L Liquid

$H_2/RP/O_2$
X/X/X Mode 1
X/X/X Mode 2

TA3-0752e

Alternate Propulsion Subsystem Concepts
FRSCC Cases

- Baseline Turbomachinery/Preburner Arrangement Selection
  - Single Chamber
    - FRSCC-7
      - Lowest Average Turbine Temperatures, Although Not Lowest Minimum Turbine Temperature
        - Tripropellant Preburner Allows Best Movement of Energy Among Turbines
        - Likely to Have Best Design Margins
      - Small Weight Penalty Over Lowest Weight Case
  - Bell Annular
    - FFSCC-6
      - Lightest Weight

TA3–0875a

Tripropellant Comparison Study

Hybrid Cycle Cases

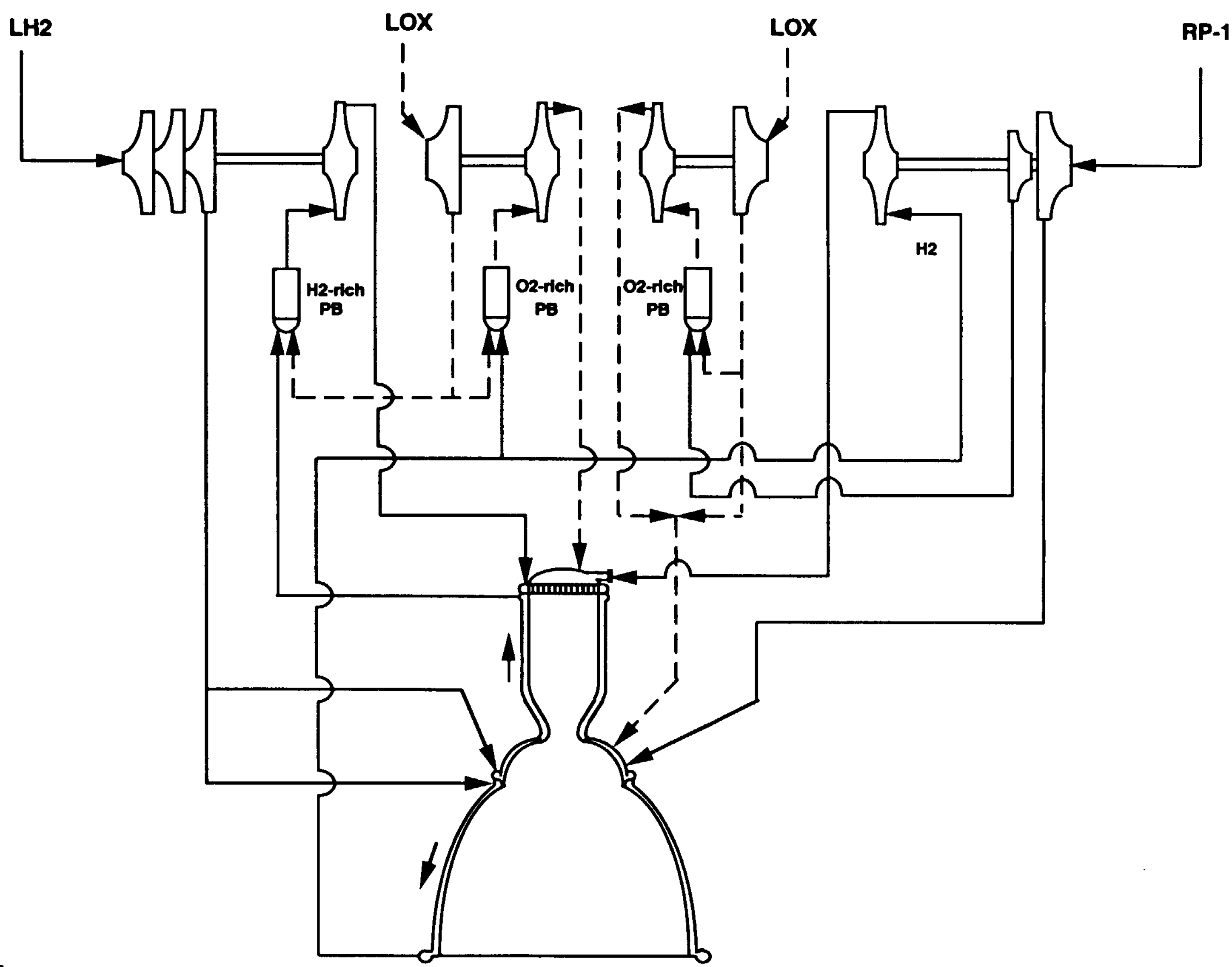
	H_2	RP	O_2 Mode 1	O_2 Mode 2	SC	Annular
Hybrid-1	H_2 Rich	H_2 Exp	O_2 Rich	O_2 Rich	—	√ L/G G/G
Hybrid-2	H_2 Rich	H_2 Exp	← O_2 Rich Combined O_2 Pump →		√ G/L/G G/G	—
Hybrid-3	H_2 Rich	← H_2 Exp Single Shaft →		O_2 Rich	√ G/L/G G/G	√ L/L G/G
Hybrid-4	H_2 Rich	← H_2 Exp Single Shaft Combined O_2 Pump →			√ G/L/G G/G	√ L/L G/G

√	Applicable	MCC Injection		H_2/RP/O_2	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3–0750a

Tripropellant Configuration Study
Hybrid-1(A) LOX/RP/H2 Engine Schematic

Annular Chamber

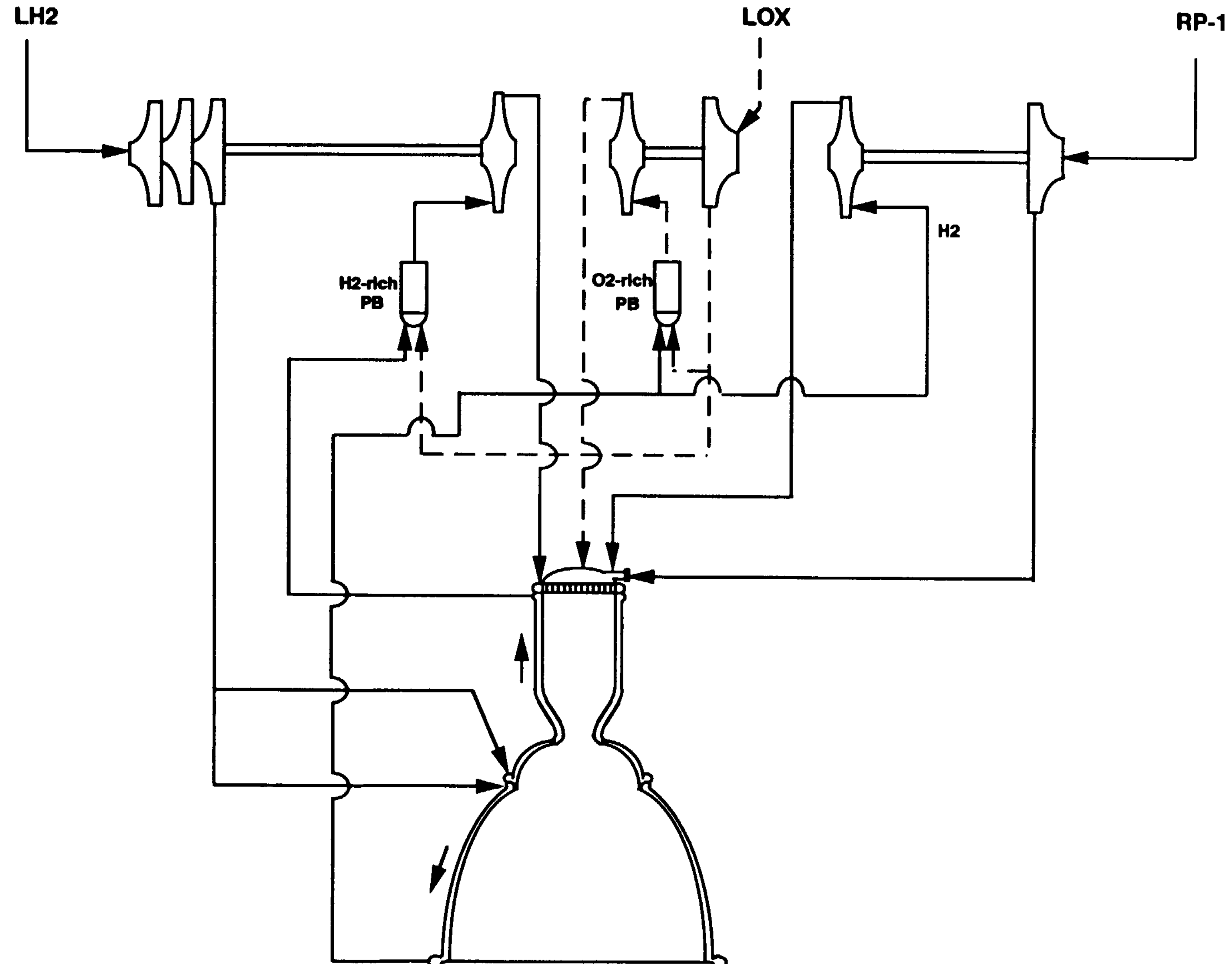


10-25-94

TA3-0634

Tripropellant Configuration Study
Hybrid-2(SC) LOX/RP/H2 Engine Schematic

Single Chamber

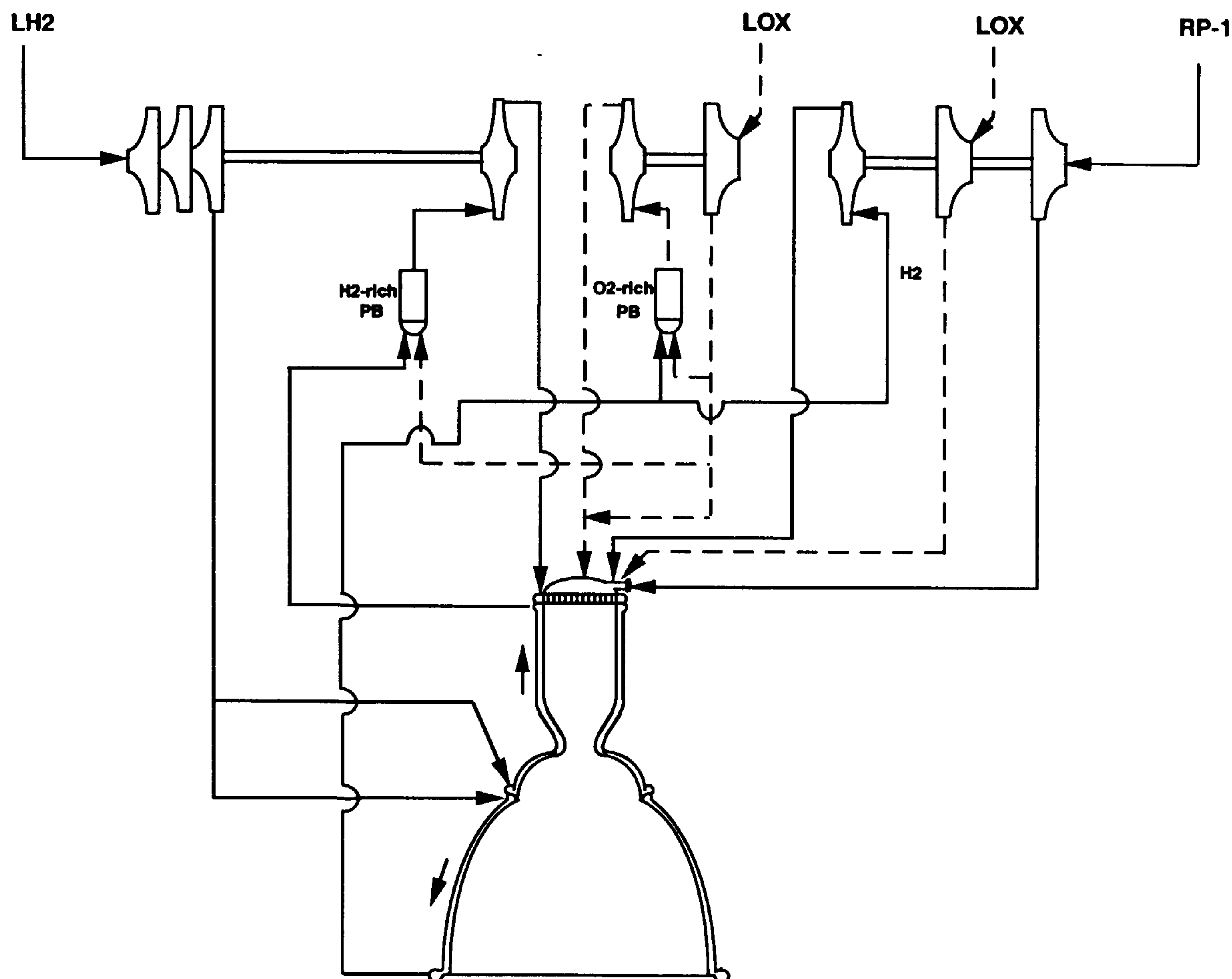


10-24-94

TA3–0835

Tripropellant Configuration Study
Hybrid-3(SC) LOX/RP/H2 Engine Schematic

Single Chamber

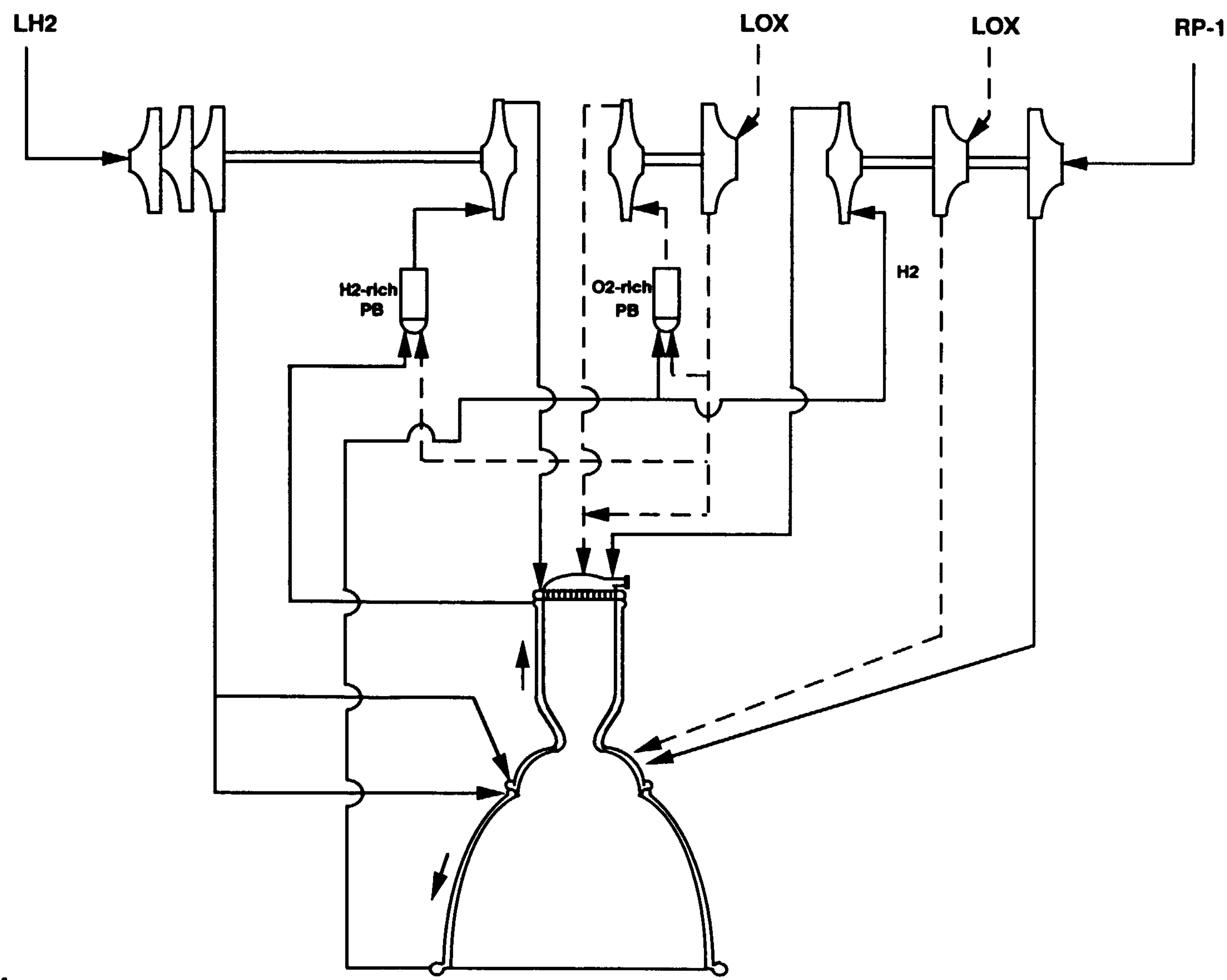


10-24-94

TA3-0836

Tripropellant Configuration Study
Hybrid-3(A) LOX/RP/H2 Engine Schematic

Annular Chamber

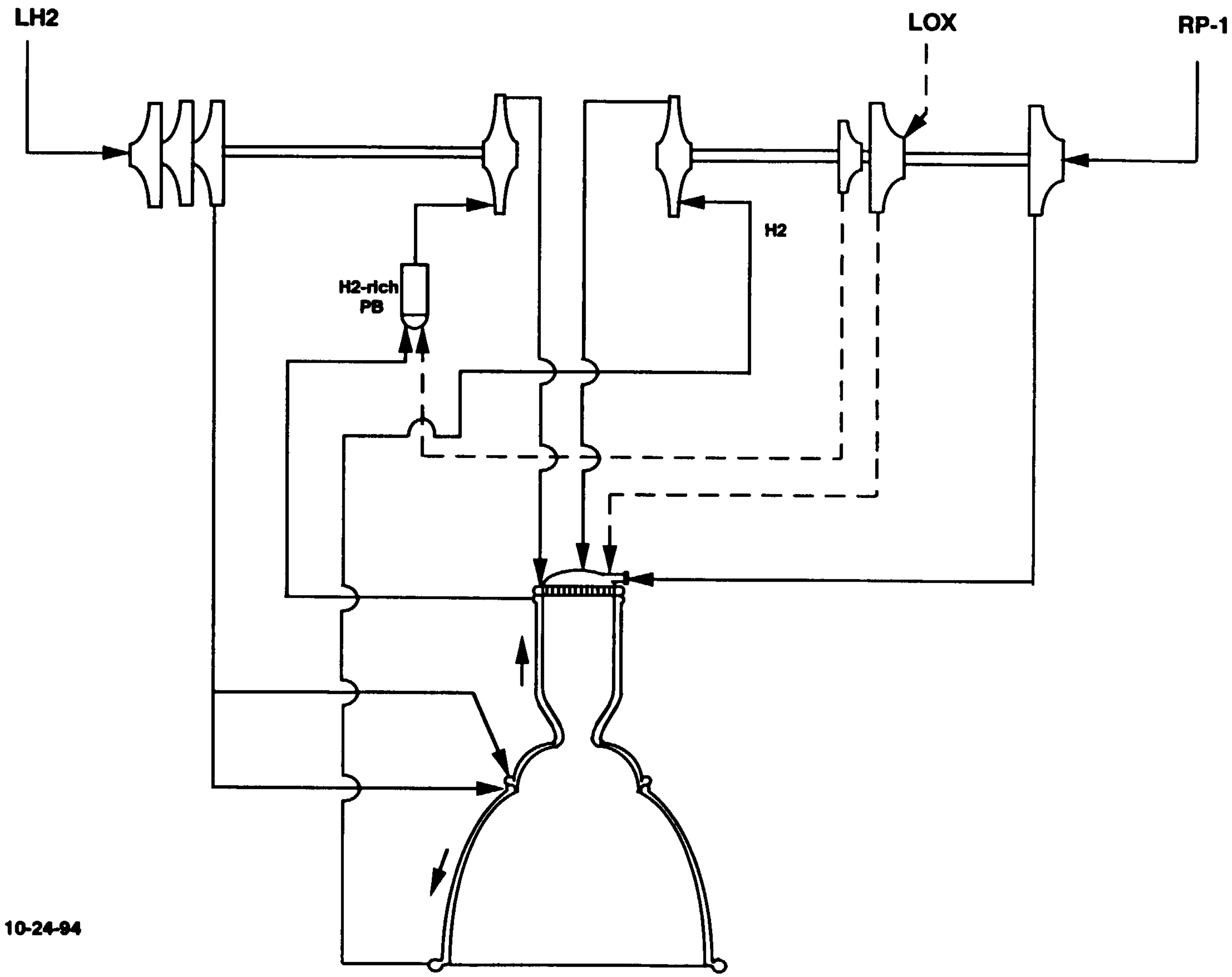


10-24-94

TA3–0837

Tripropellant Configuration Study
Hybrid-4(SC) LOX/RP/H2 Engine Schematic

Single Chamber

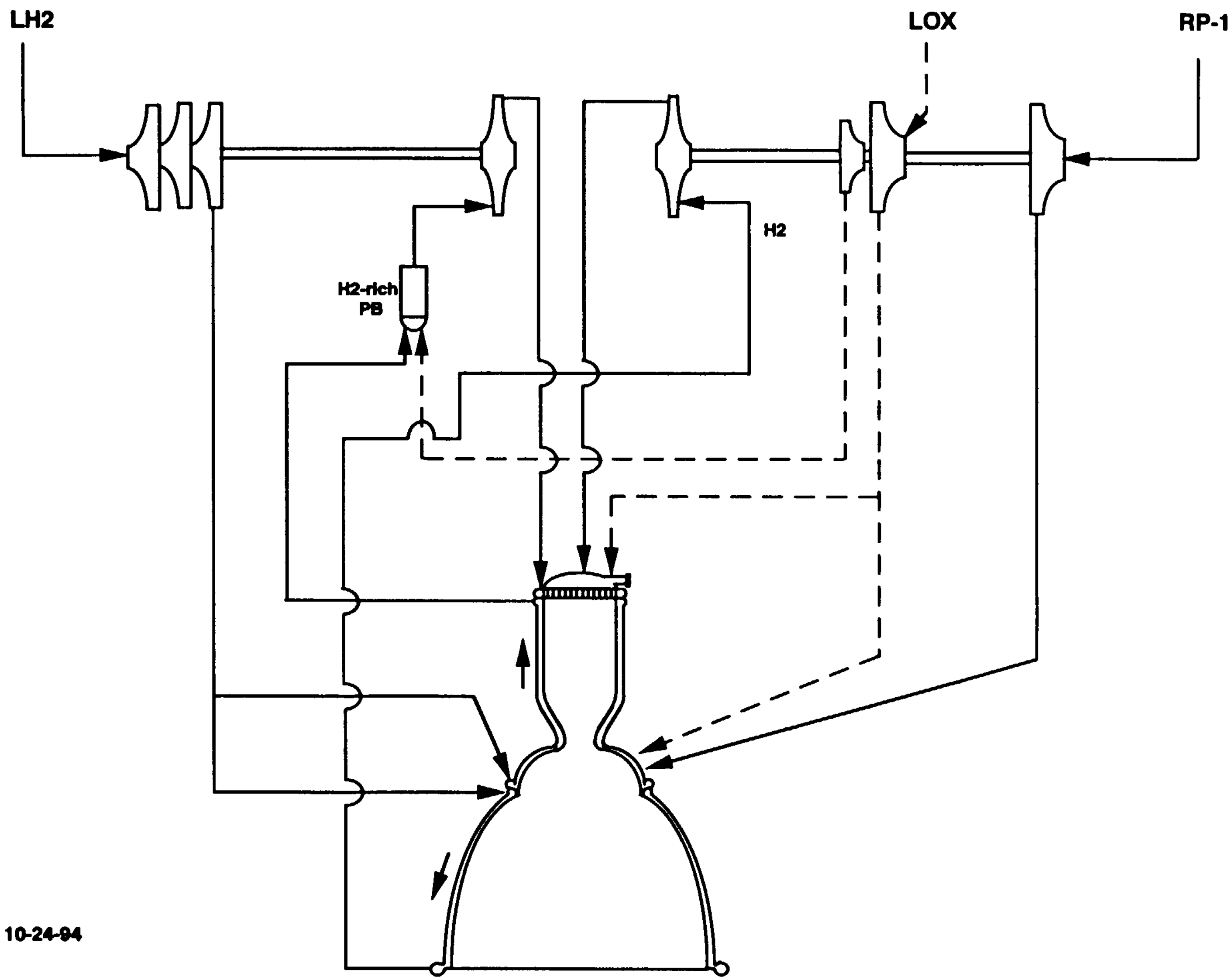


10-24-94

TA3–0838

Tripropellant Configuration Study
Hybrid-4(A) LOX/RP/H2 Engine Schematic

Annular Chamber



10-24-94

TA3–0839

Tripropellant Comparison Study
Hybrid Cycle Cases

	Cycle (Relative Weight) (SC/Annular)	H_2 (Tur Temp, °R)	RP (Tur Temp, °R)	O_2 Mode 1 (Tur Temp, °R)	O_2 Mode 2 (Tur Temp, °R)	SC	Annular
√	Hybrid-1 (— / 1.000)	H_2 Rich 1,700	H_2 Exp 1,000	O_2 Rich 1,100	O_2 Rich 1,100	—	√ L/G G/G
	Hybrid-2 (1.090 / —)	H_2 Rich 1,243	H_2 Exp 997	← O_2 Rich Combined O_2 Pump 1,100 →		√ G/L/G G/G	—
√ (SC)	Hybrid-3 (1.000 / **)	H_2 Rich 1,700	← H_2 Exp Single Shaft 1,000 →		O_2 Rich 1,100	√ G/L/G G/G	√ L/L G/G
	Hybrid-4 (* / *)	H_2 Rich	← H_2 Exp Single Shaft Combined O_2 Pump →			√ G/L/G G/G	√ L/L G/G

* Balance only to ≤ 3,000 psi.
** Excessive H_2 turbine temperature due to expander H_2 drawdown for horsepower of O_2 pump.

√	Applicable	MCC Injection		$H_2/RP/O_2$	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3–0750e

Alternate Propulsion Subsystem Concepts
Hybrid Cycle Cases

- Baseline Turbomachinery/Preburner Arrangement Selection
  - Single Chamber
    - Hybrid-3
      - Lightest Weight
      - Hybrid-2 Has Considerably Lower Temperatures But the Weight Penalty is Too High
  - Bell Annular
    - Hybrid-1
      - Lightest Weight
      - Only Viable Bell Annular System

TA3–0875c

Tripropellant Comparison Study
Bipropellant Cycles

TA3–0863b

Tripropellant Comparison Study

Bipropellant Cycle Cases

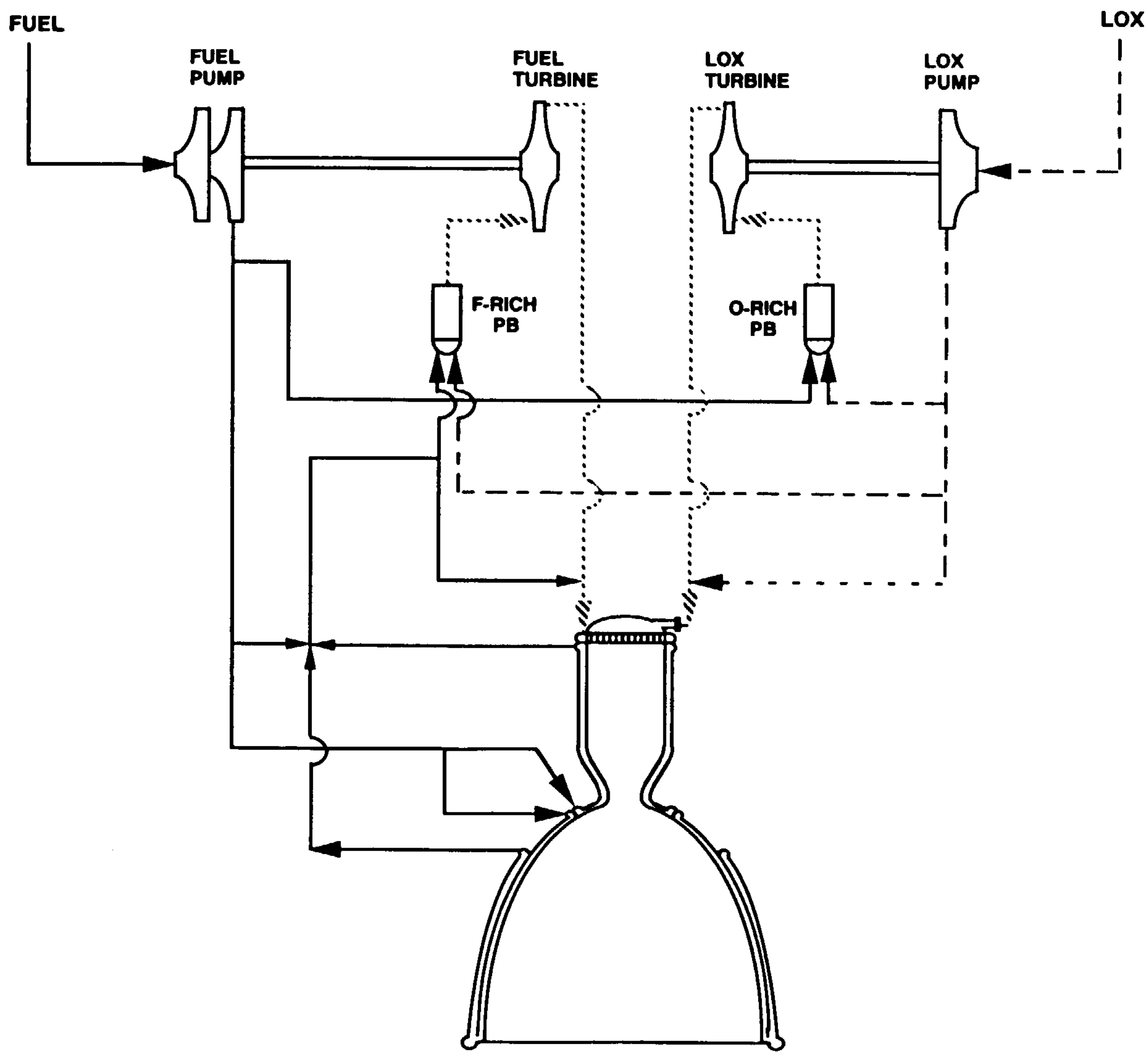
	H_2	RP	O_2 Mode 1	O_2 Mode 2	SC	Annular
FFSCC	H_2 Rich	—	—	O_2 Rich	√ — G/G	—
SCC (FR)	H_2 Rich	—	—	H_2 Rich	√ — G/L	—
Hybrid	H_2 Rich	—	—	H_2 Exp	√ — G/L	—
GG	H_2 Rich	—	—	H_2 Rich	√ — G/L	—

√	Applicable	MCC Injection		$H_2/RP/O_2$	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3–1118

FFSCC Mixed Preburner Engine

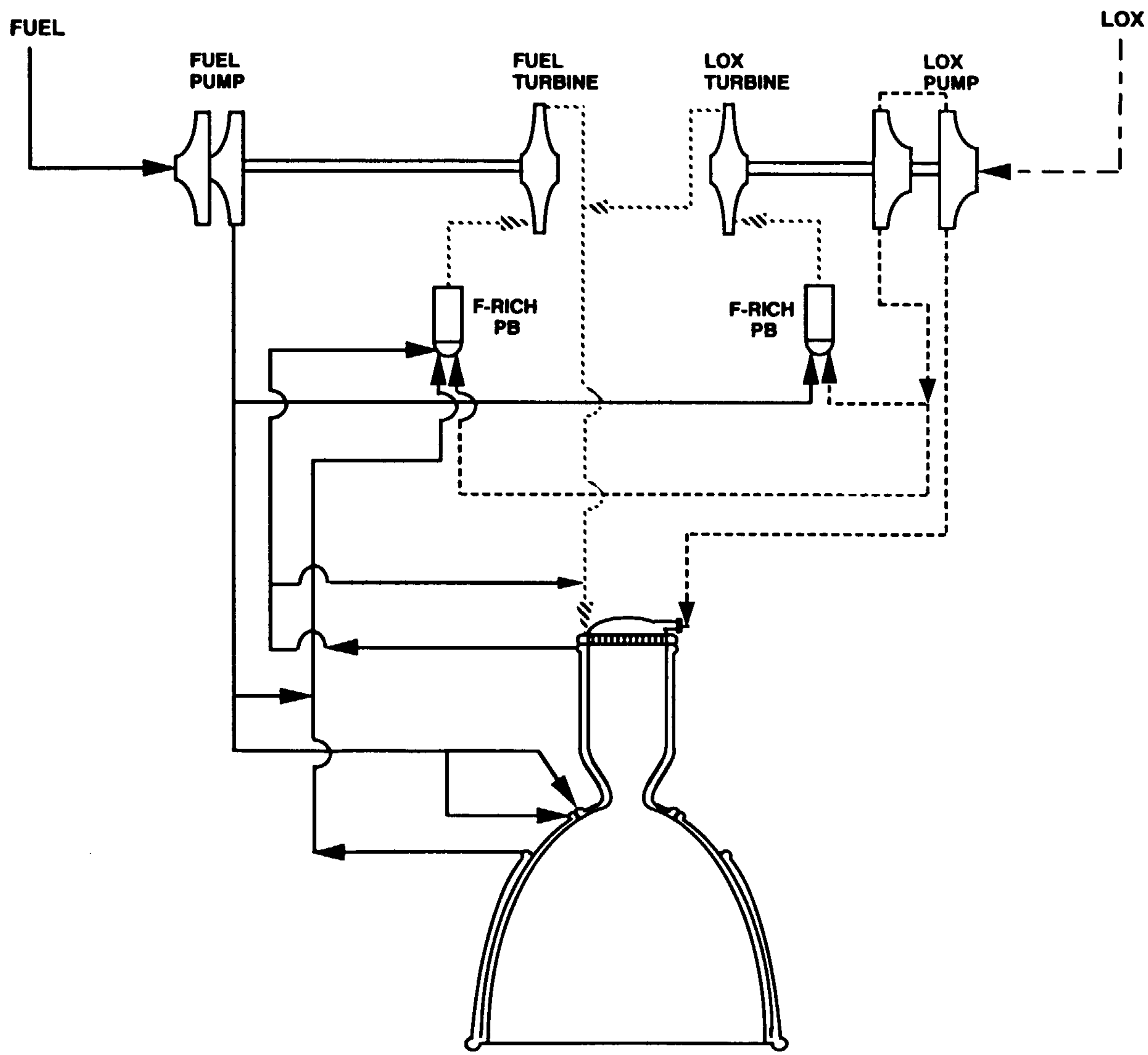
Regen Cooled MCC and Nozzle



TA3–0487f

SCC Dual Fuel-Rich Preburner Engine

Regen Cooled MCC and Nozzle

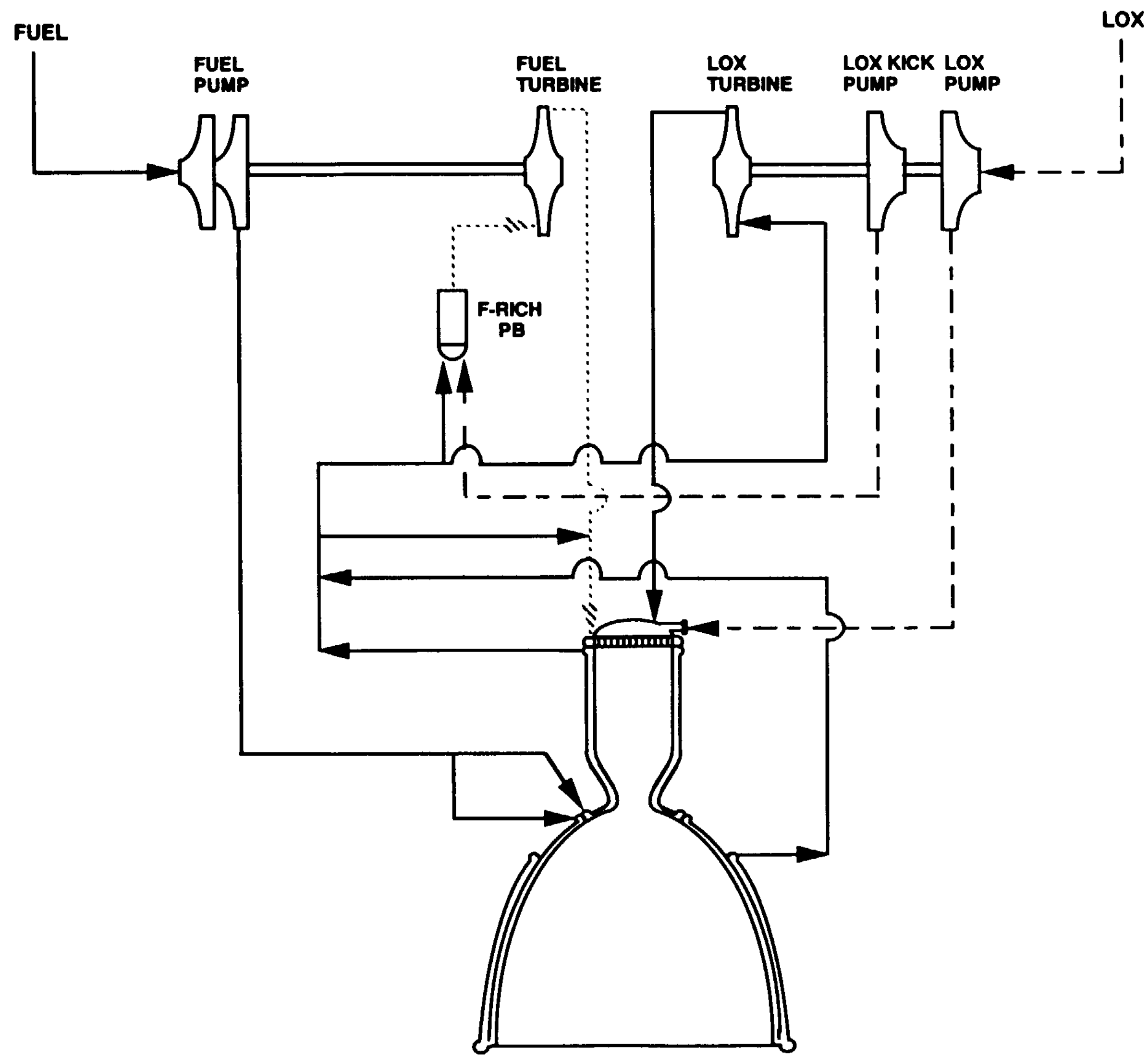


TA3–0518a

Alternate Propulsion Subsystem Concepts
Bipropellant Cycles

Hybrid Cycle Engine

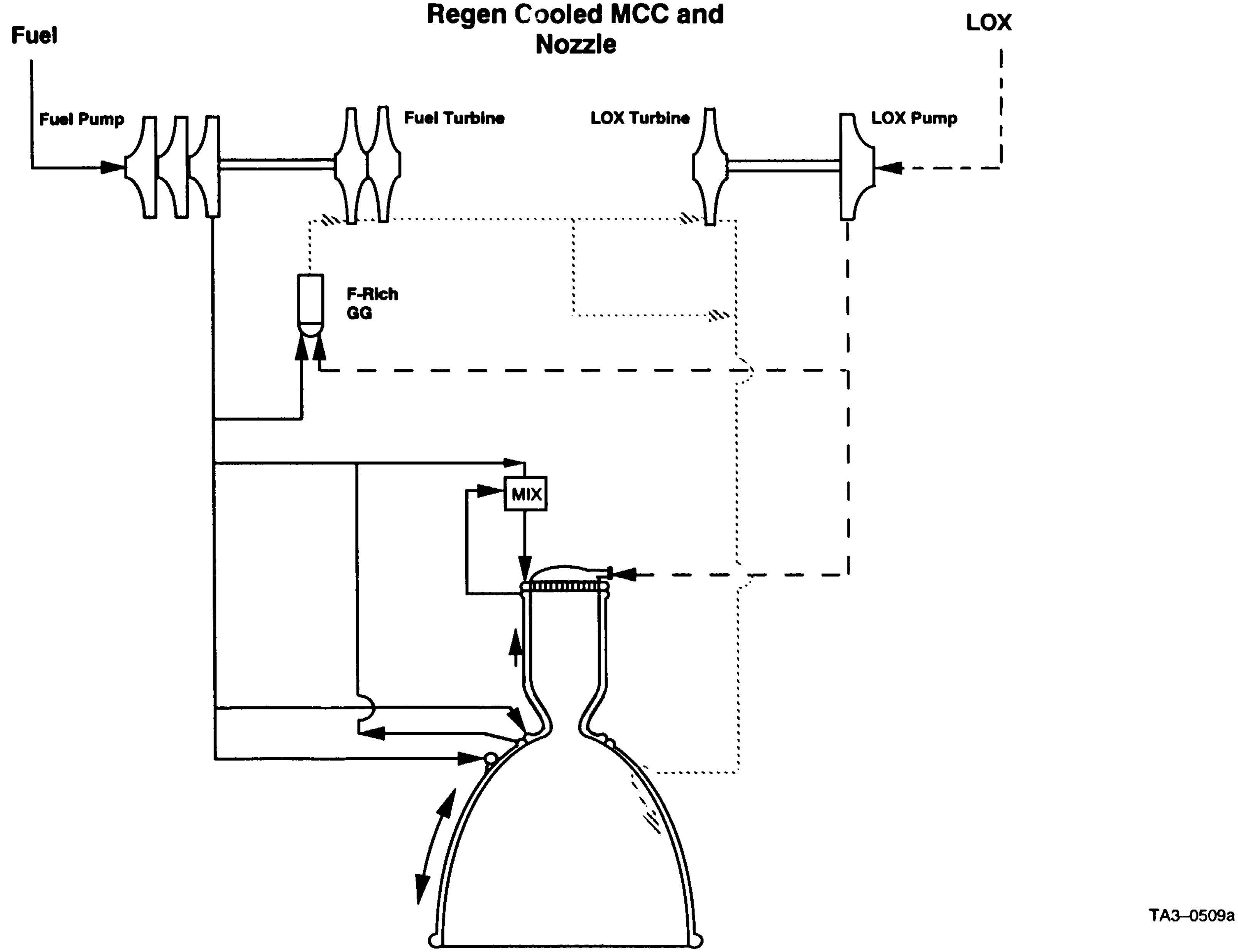
(Fuel Side Preburner, Ox Side Expander)
Regen Cooled MCC and Nozzle



TA3–0490c

Alternate Propulsion Subsystem Concepts
Bipropellant Cycles

Gas Generator Cycle
Regen Cooled MCC and Nozzle



Tripropellant Comparison Study
Bipropellant Cycle Cases

	H_2	RP	O_2 Mode 1	O_2 Mode 2	SC	Annular
FFSCC	H_2 Rich 1,150	—	—	O_2 Rich 1,100	√ — G/G	—
SCC (FR)	H_2 Rich 1,400	—	—	H_2 Rich 1,100	√ — G/L	—
Hybrid	H_2 Rich 1,700	—	—	H_2 Exp 614	√ — G/L	—
GG	H_2 Rich 1,900	—	—	H_2 Rich 1,357	√ — G/L	—

√	Applicable	MCC Injection		H_2/RP/O_2	
—	Not Applicable	G	Gas	X/X/X	Mode 1
SC	Single Chamber	L	Liquid	X/X/X	Mode 2

TA3–1118a

Tripropellant Comparison Study
Operating Parameter Determination

TA3–0863c

Alternate Propulsion Subsystem Concepts
Tripropellant Configuration Study
Operating Parameter Choices

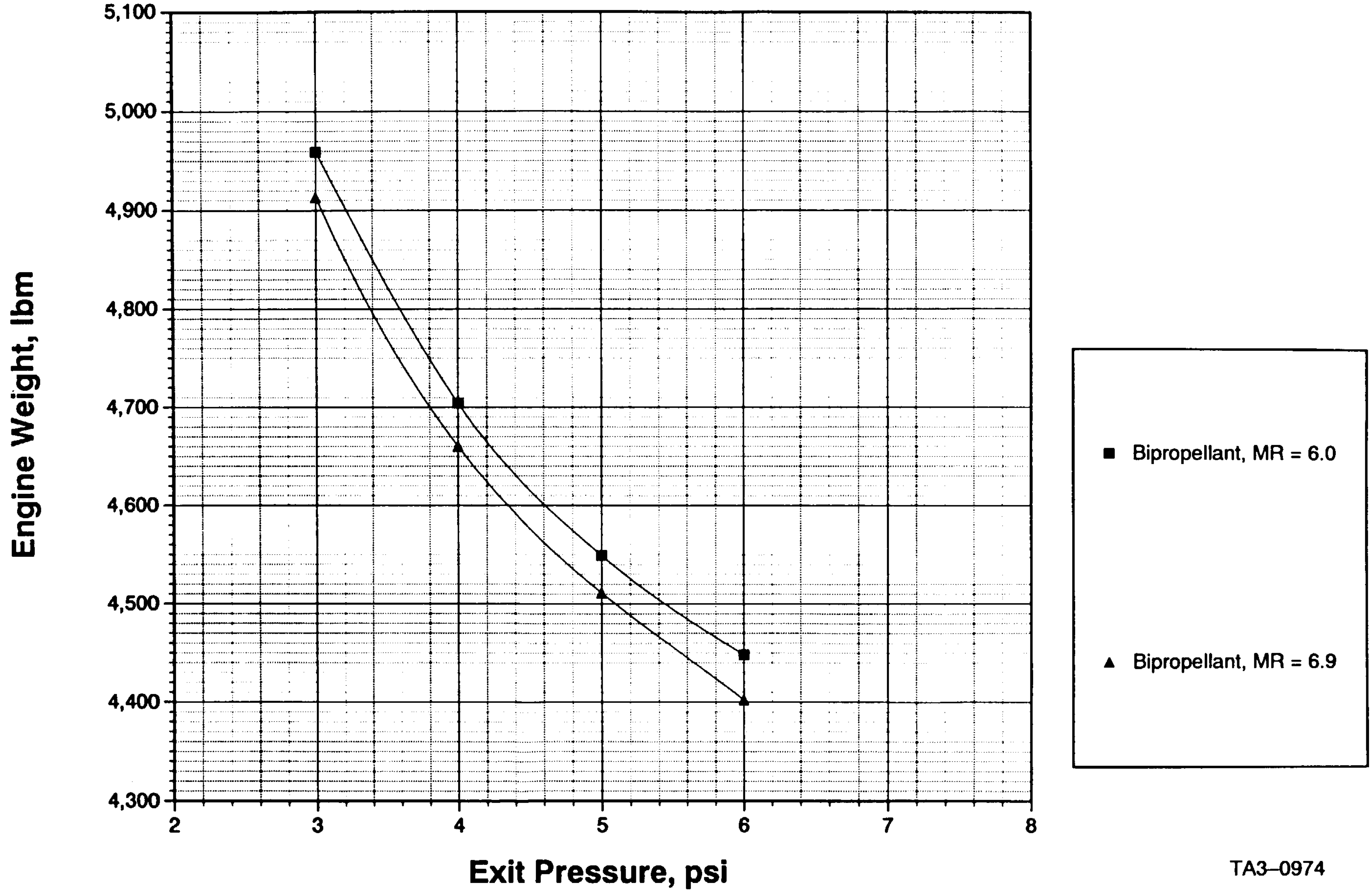
- Nozzle Exit Pressure
    - Bipropellant
    - Bell Annular
    - Single Chamber
- Bipropellant Mixture Ratio
- Bell Annular Thrust Split
- Bell Annular Mode 2 Mixture Ratio
- Bell Annular Mode 1 Mixture Ratio
- Single Chamber Percent Hydrogen
- Single Chamber Mode 1 Mixture Ratio
- Single Chamber Mode 2 Mixture Ratio

TA3–0864

Nozzle Exit Pressure

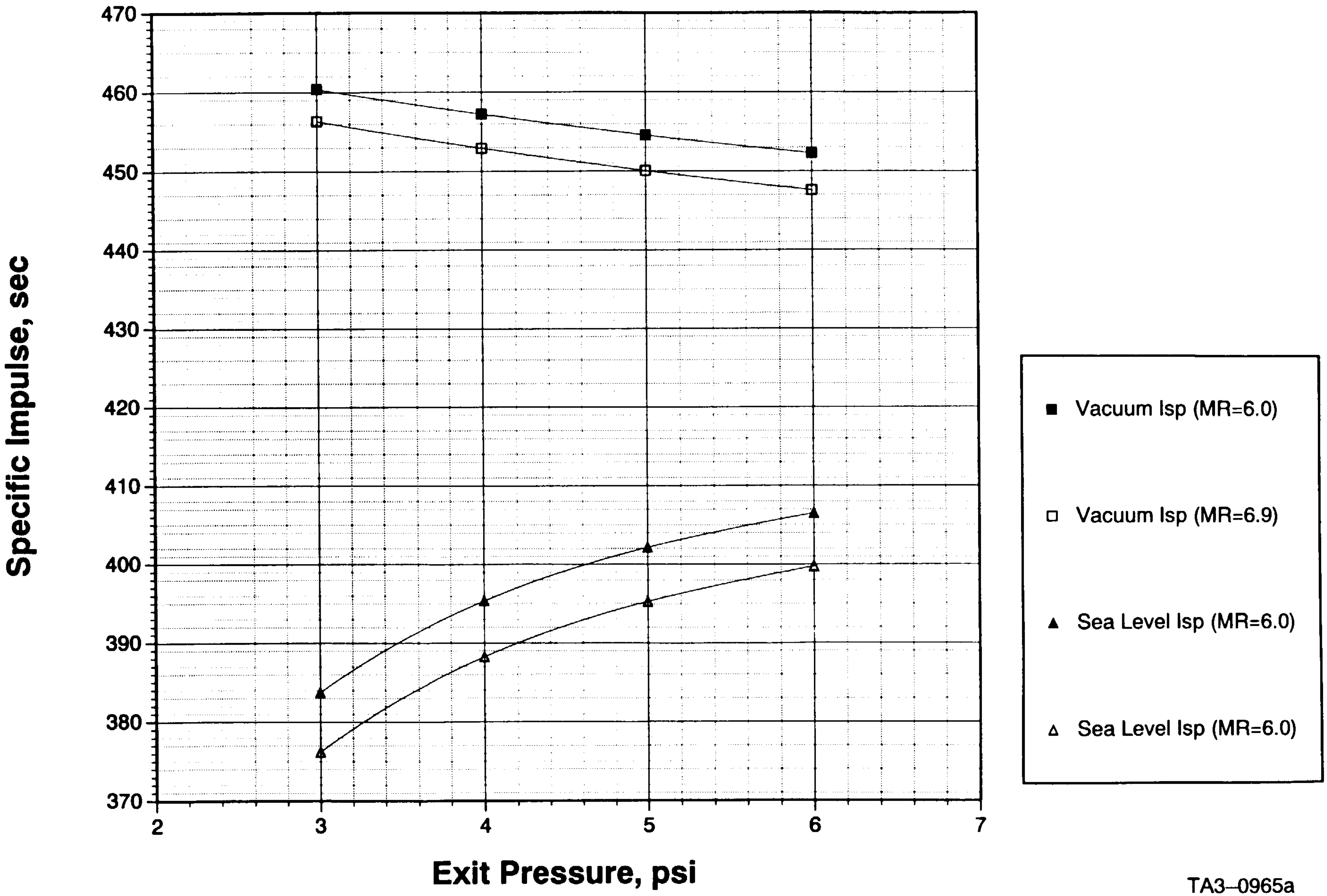
TA3–0863g

Engine Weights – Bipropellant FFSCC
Nozzle Exit Pressure Variation



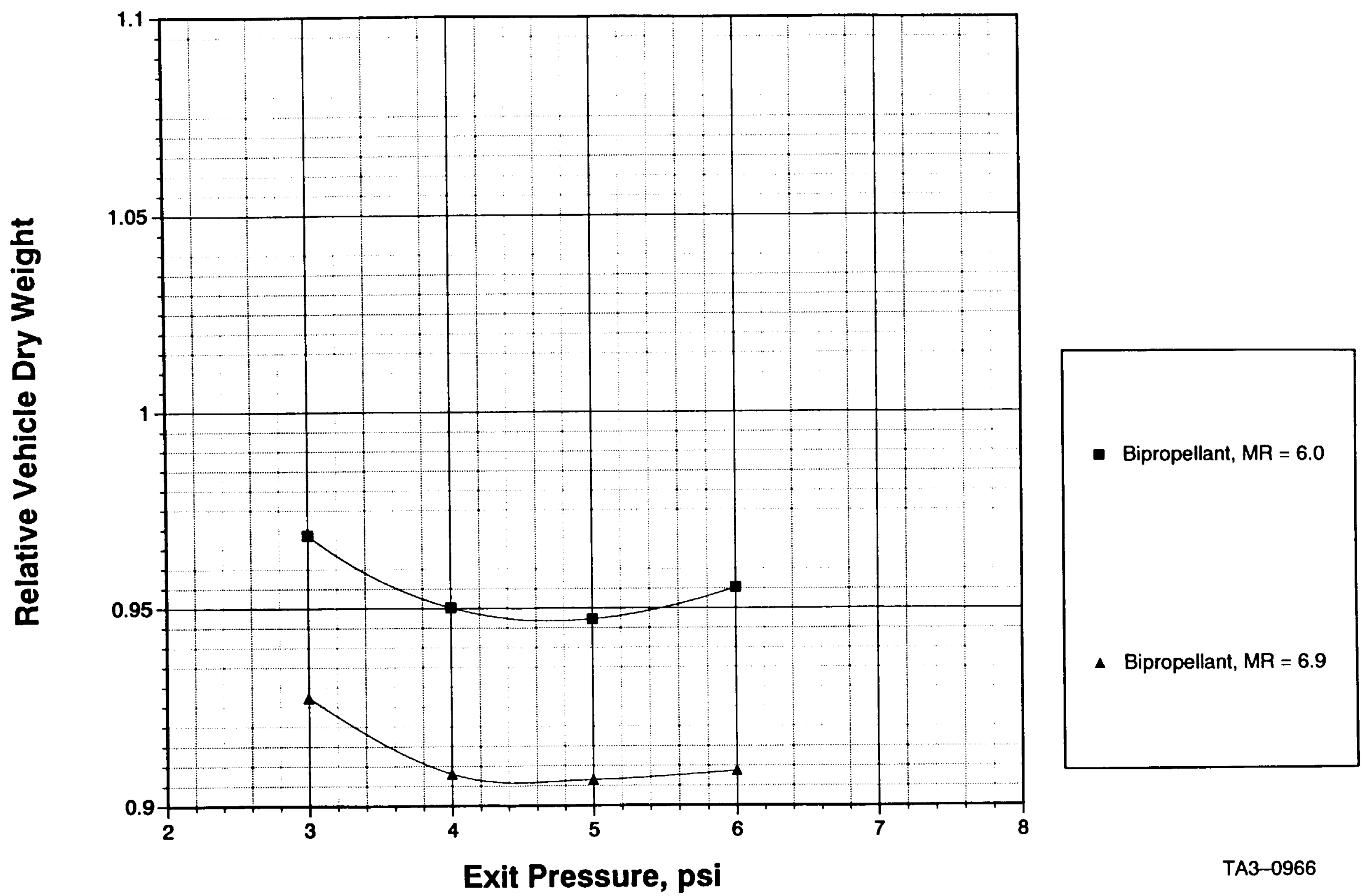
TA3–0974

Engine Performance – Bipropellant FFSCC
Nozzle Exit Pressure Variation



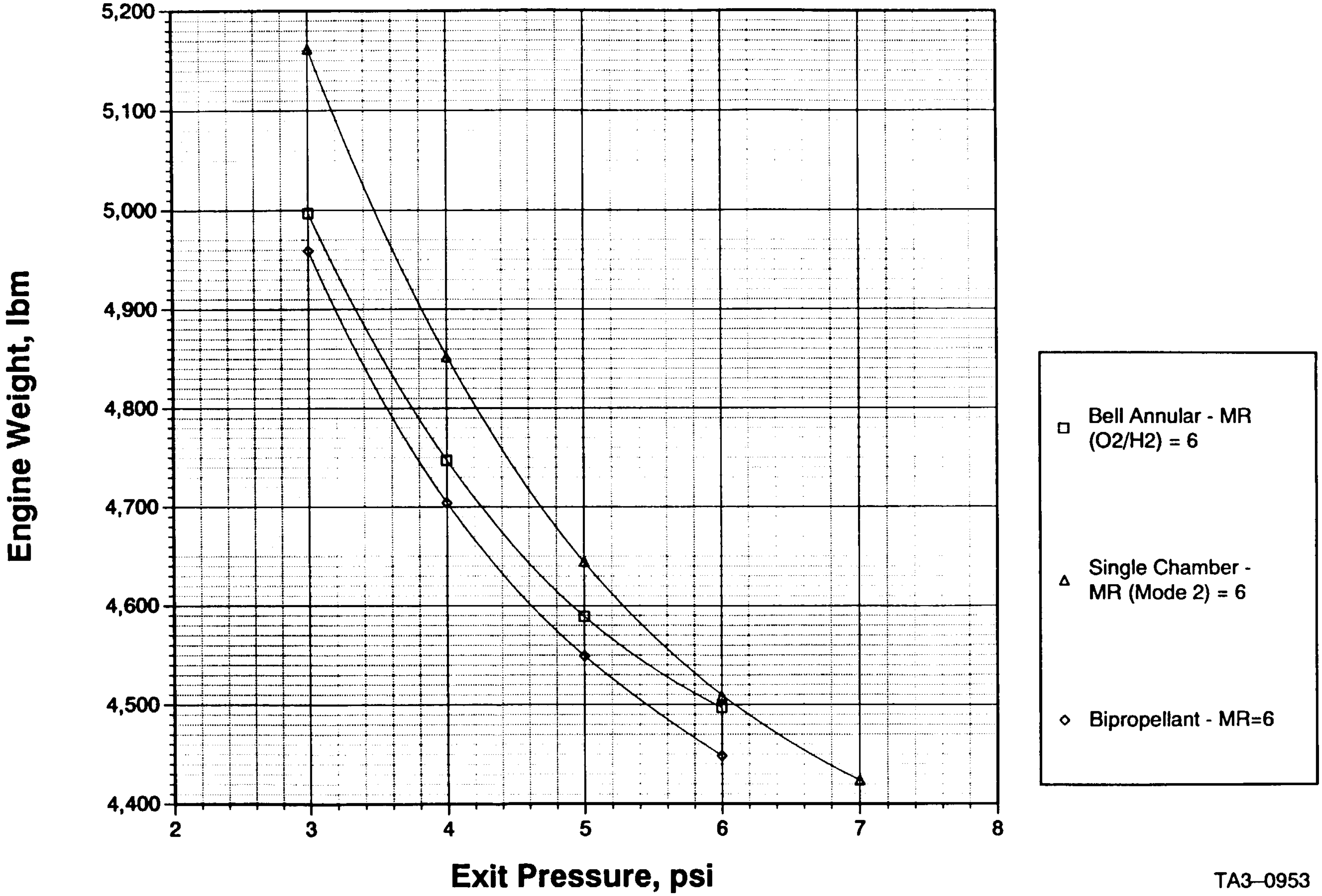
TA3–0965a

SSTO Performance – Bipropellant FFSCC
Nozzle Exit Pressure Variation



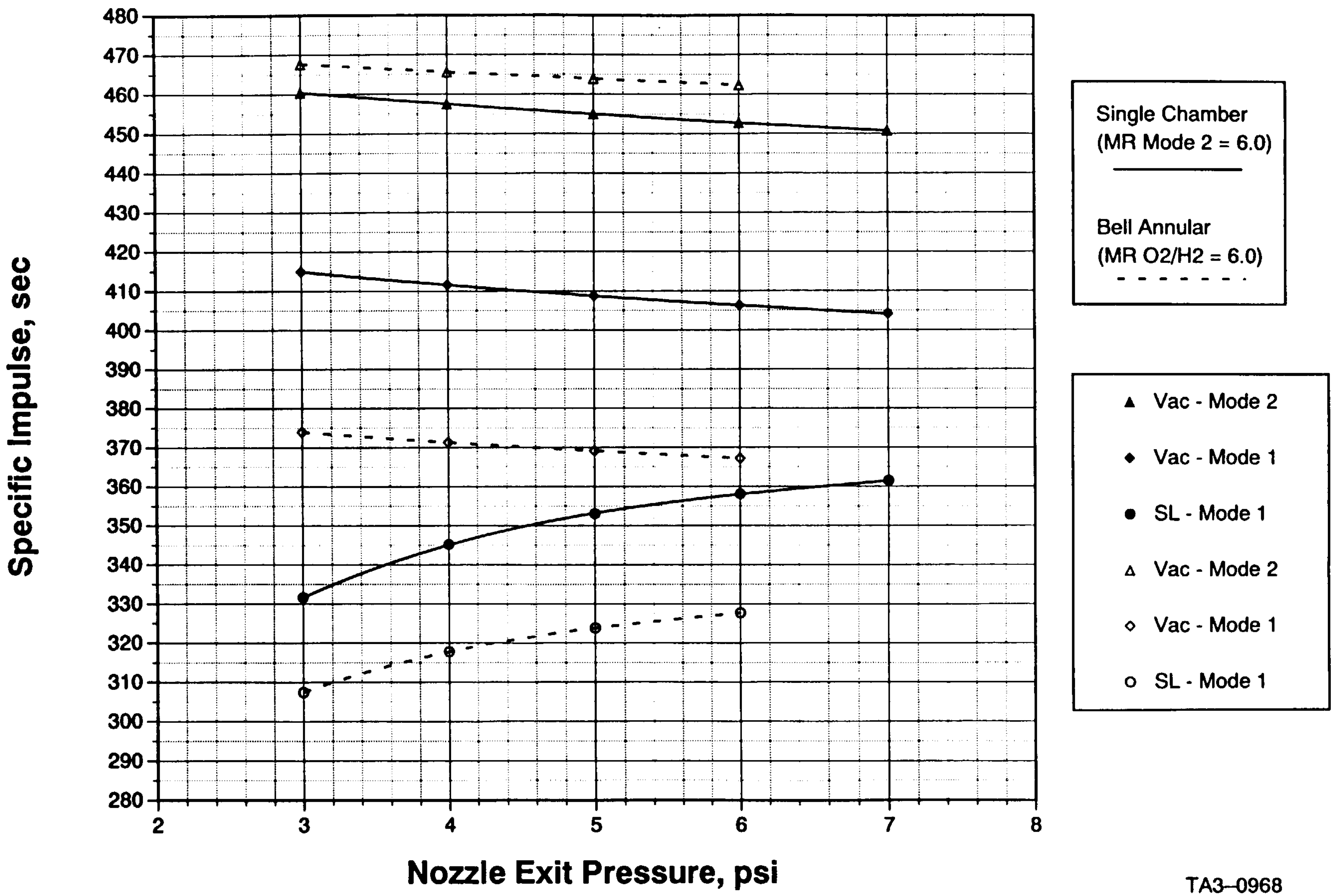
TA3–0966

Engine Weights – FFSCC
Nozzle Exit Pressure Variation



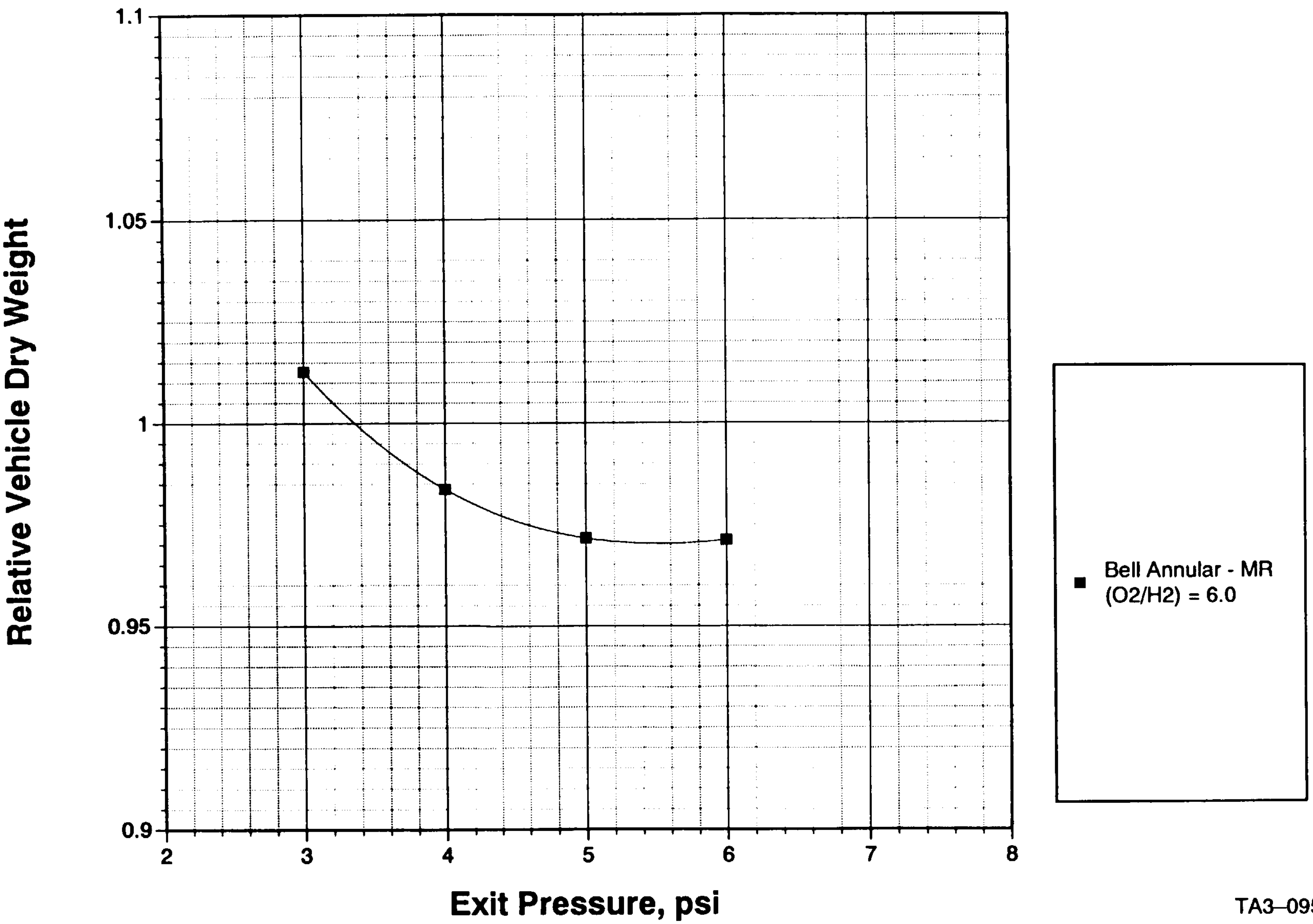
TA3–0953

Engine Performance – FFSCC Tripropellant



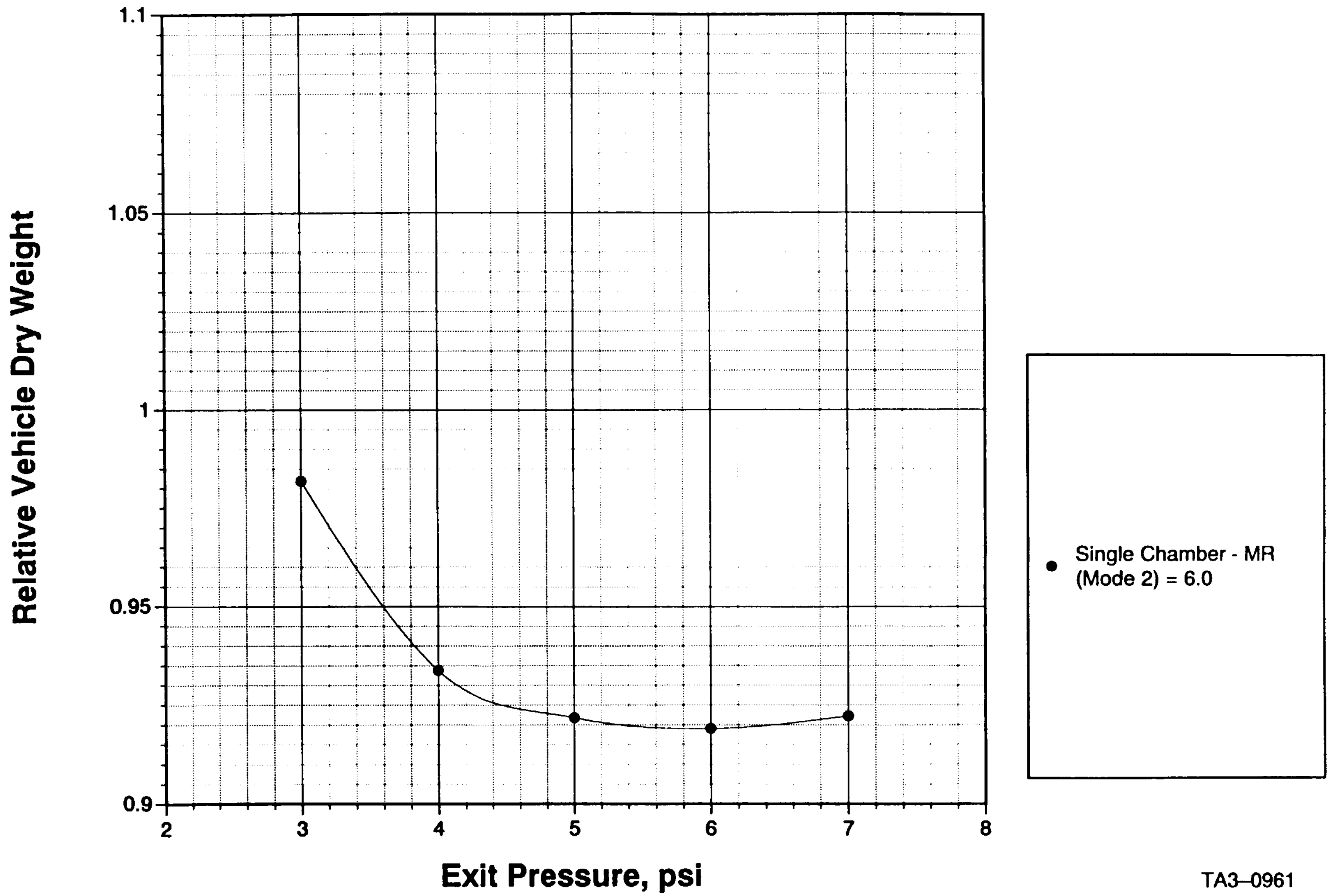
TA3–0968

SSTO Performance – Tripropellant – FFSCC
Nozzle Exit Pressure Variation



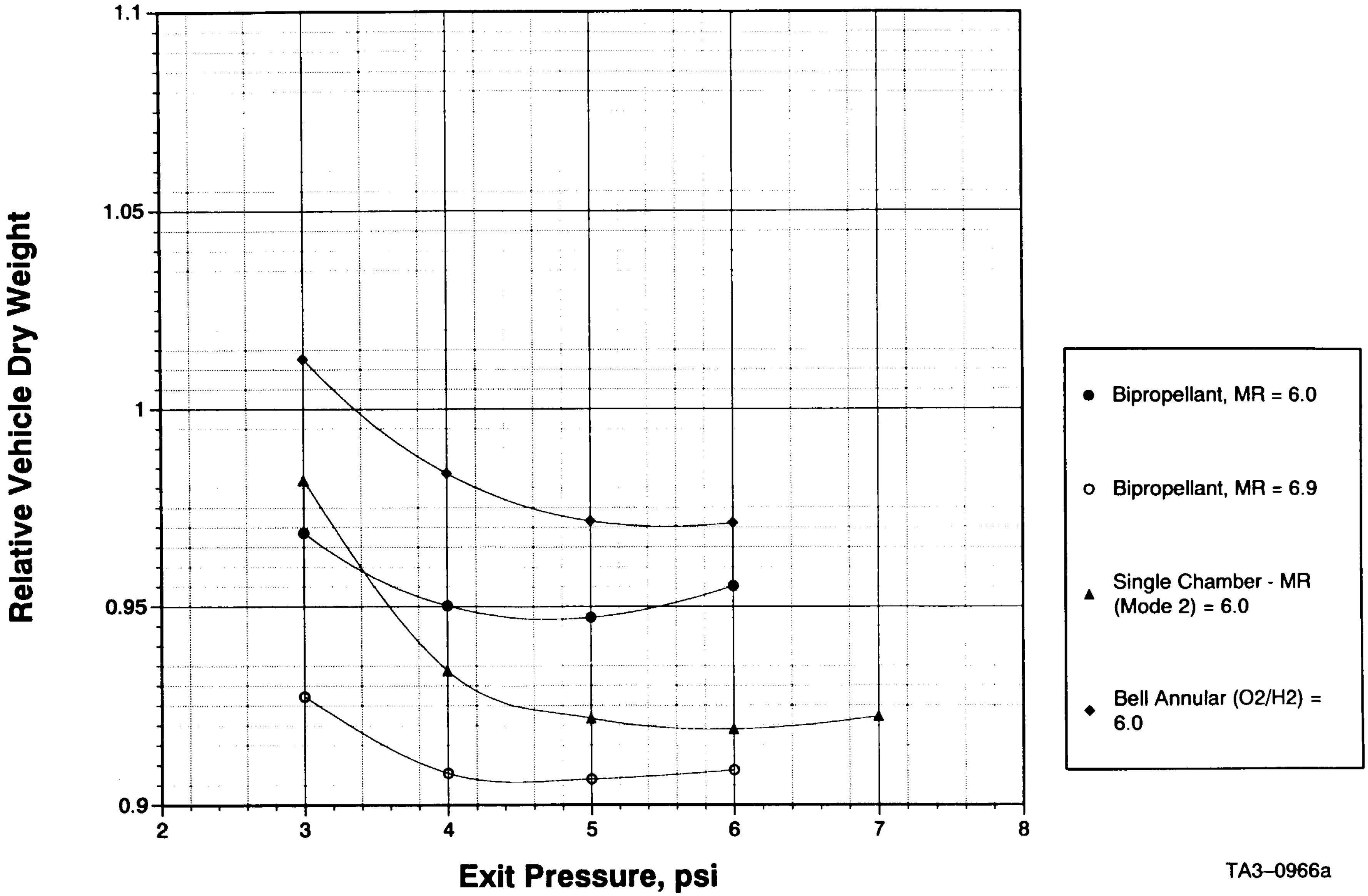
TA3–0959

SSTO Performance – Tripropellant – FFSCC
Nozzle Exit Pressure Variation



TA3–0961

SSTO Performance
Nozzle Exit Pressure Variation

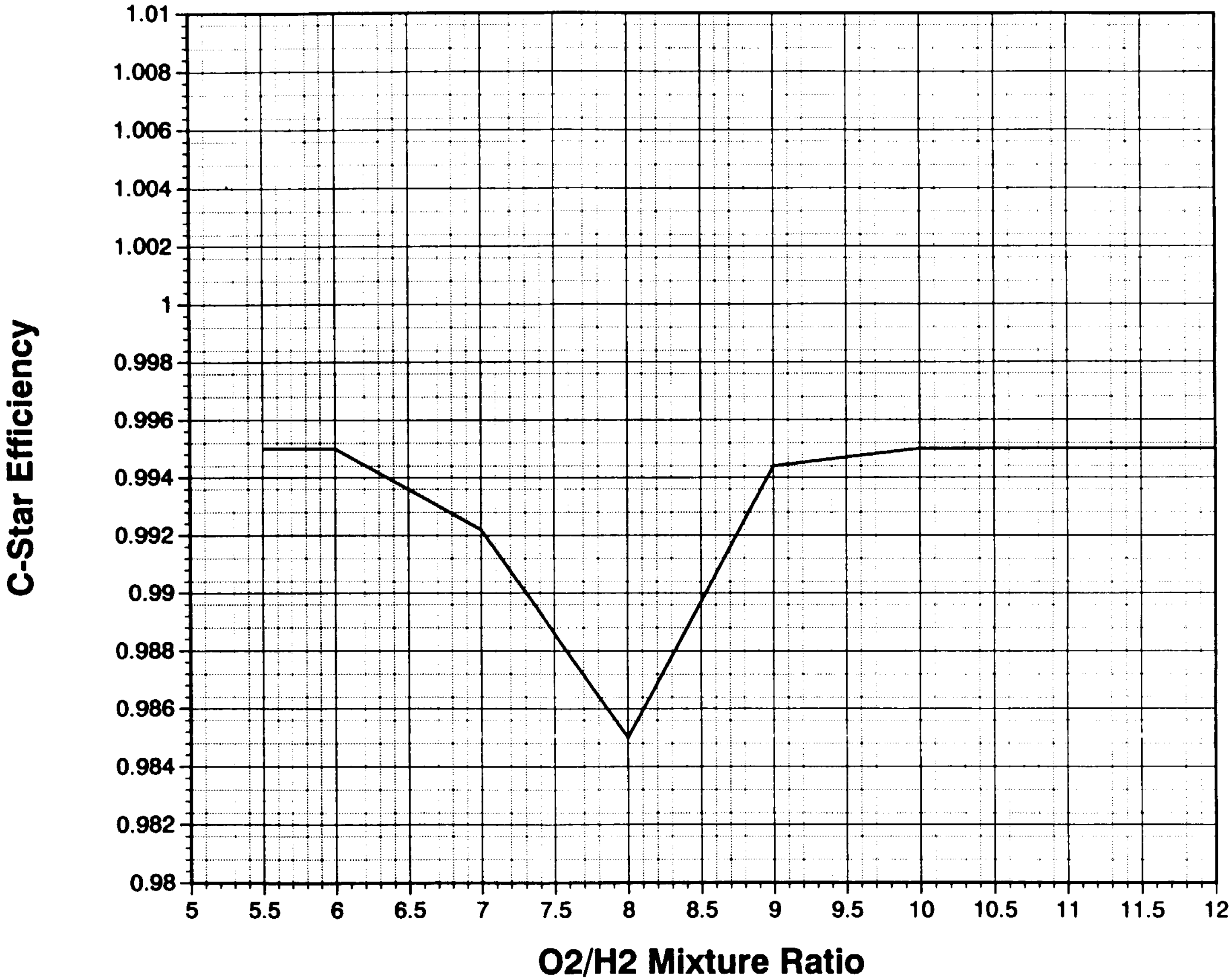


TA3–0966a

Bipropellant Mixture Ratio

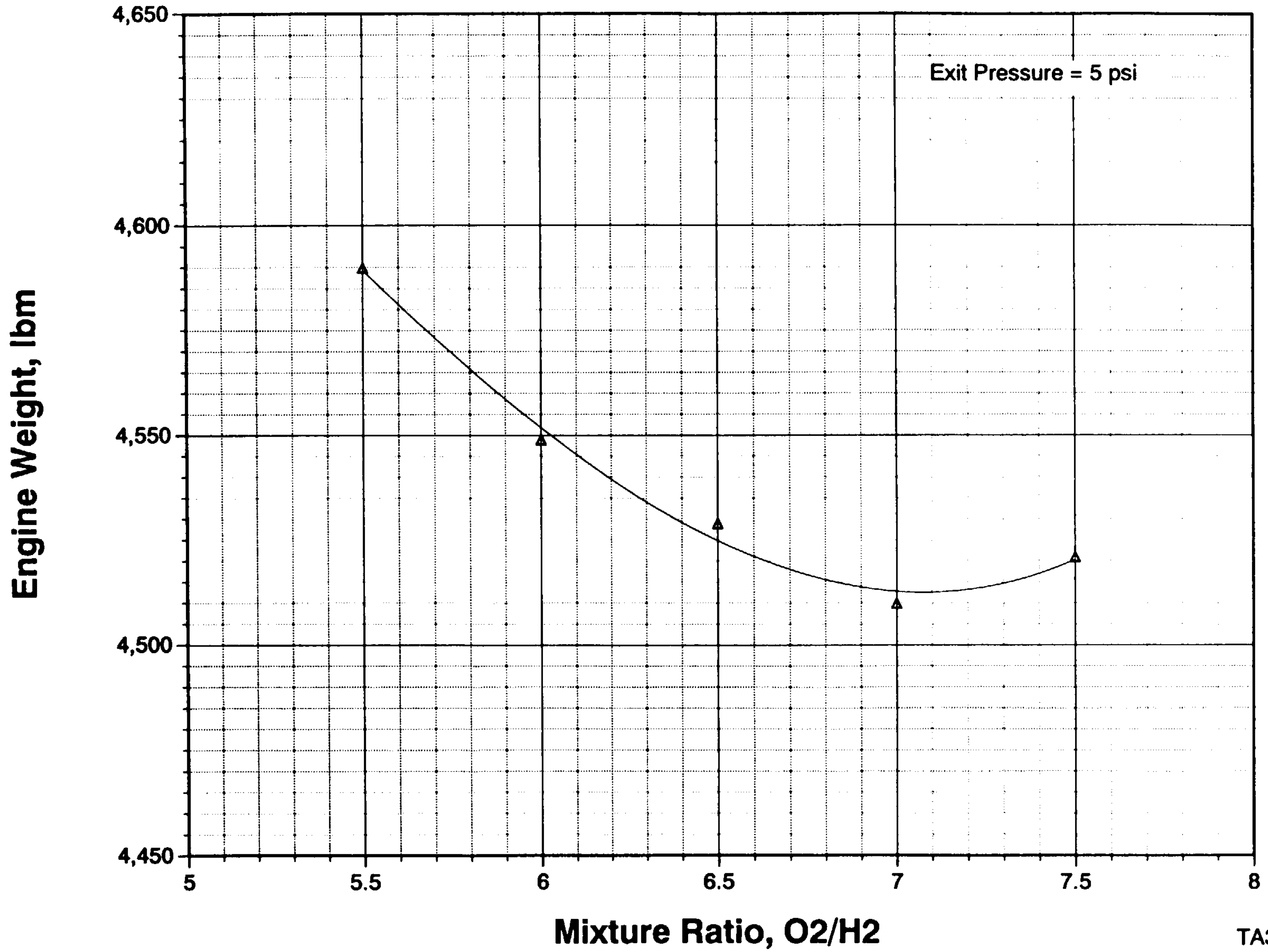
TA3–0863i

C-Star Efficiency
Bipropellant O_2/H_2



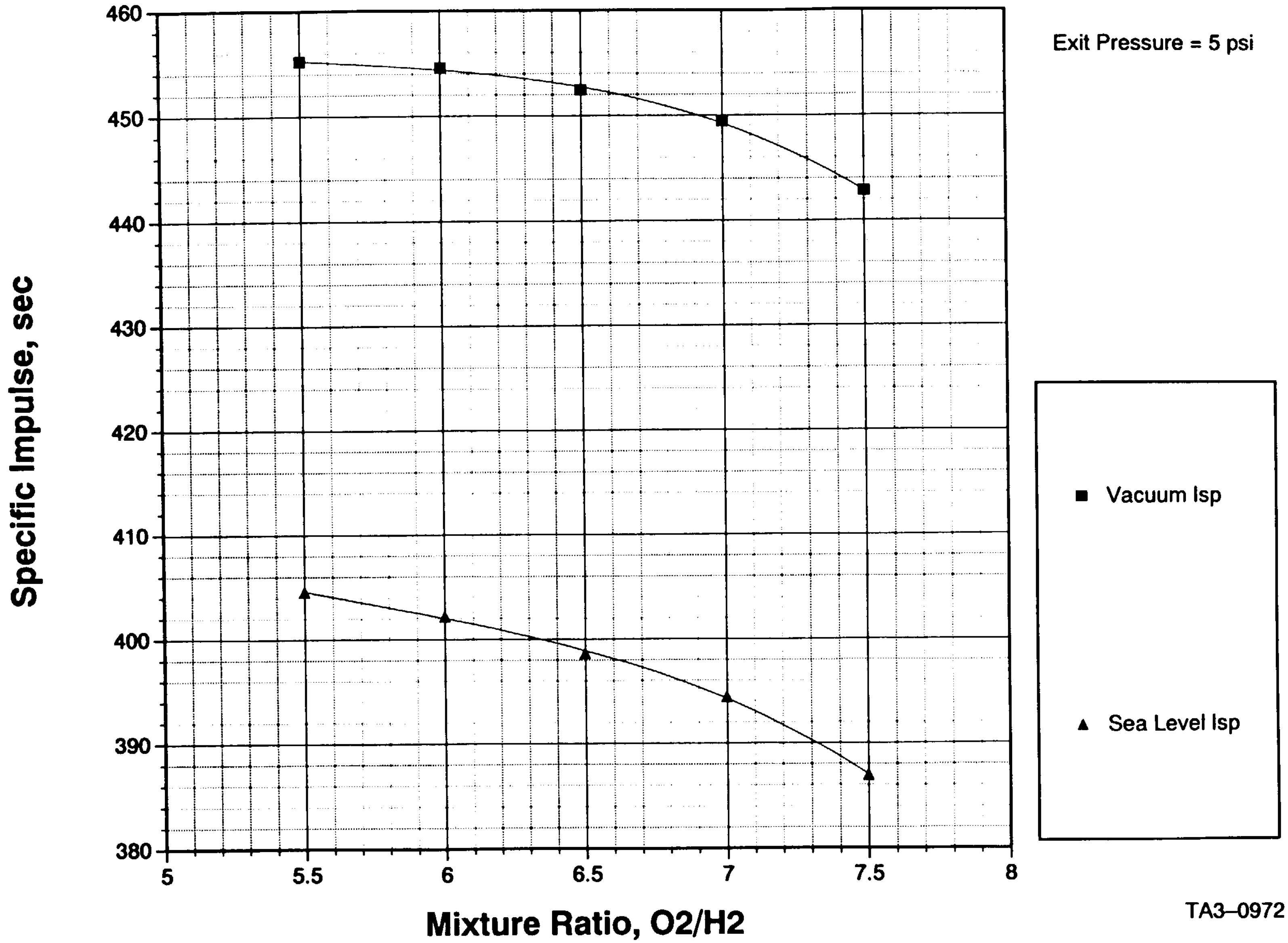
TA3–0945

Engine Weights – FFSCC Bipropellant



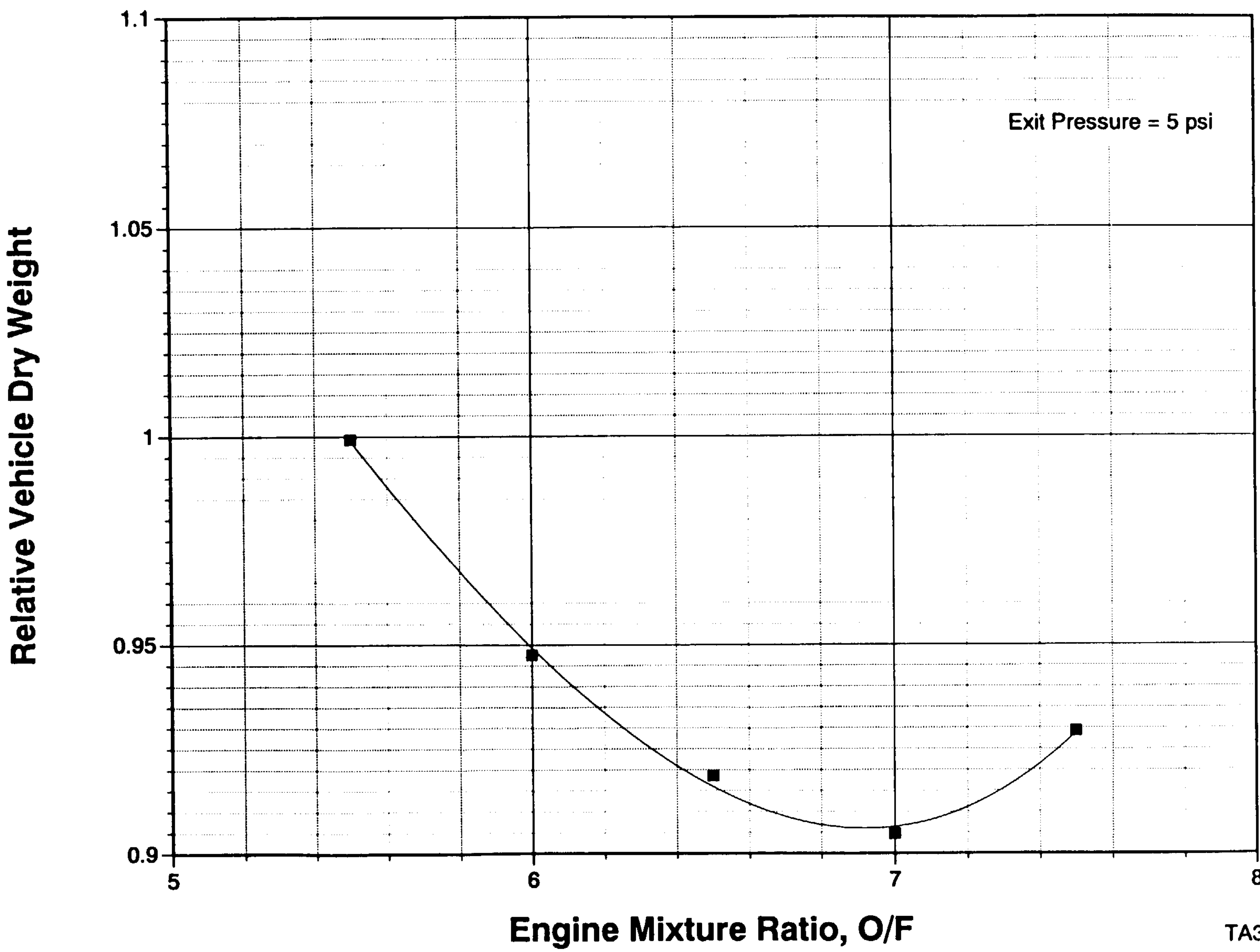
TA3–0969

Engine Performance – FFSCC Bipropellant



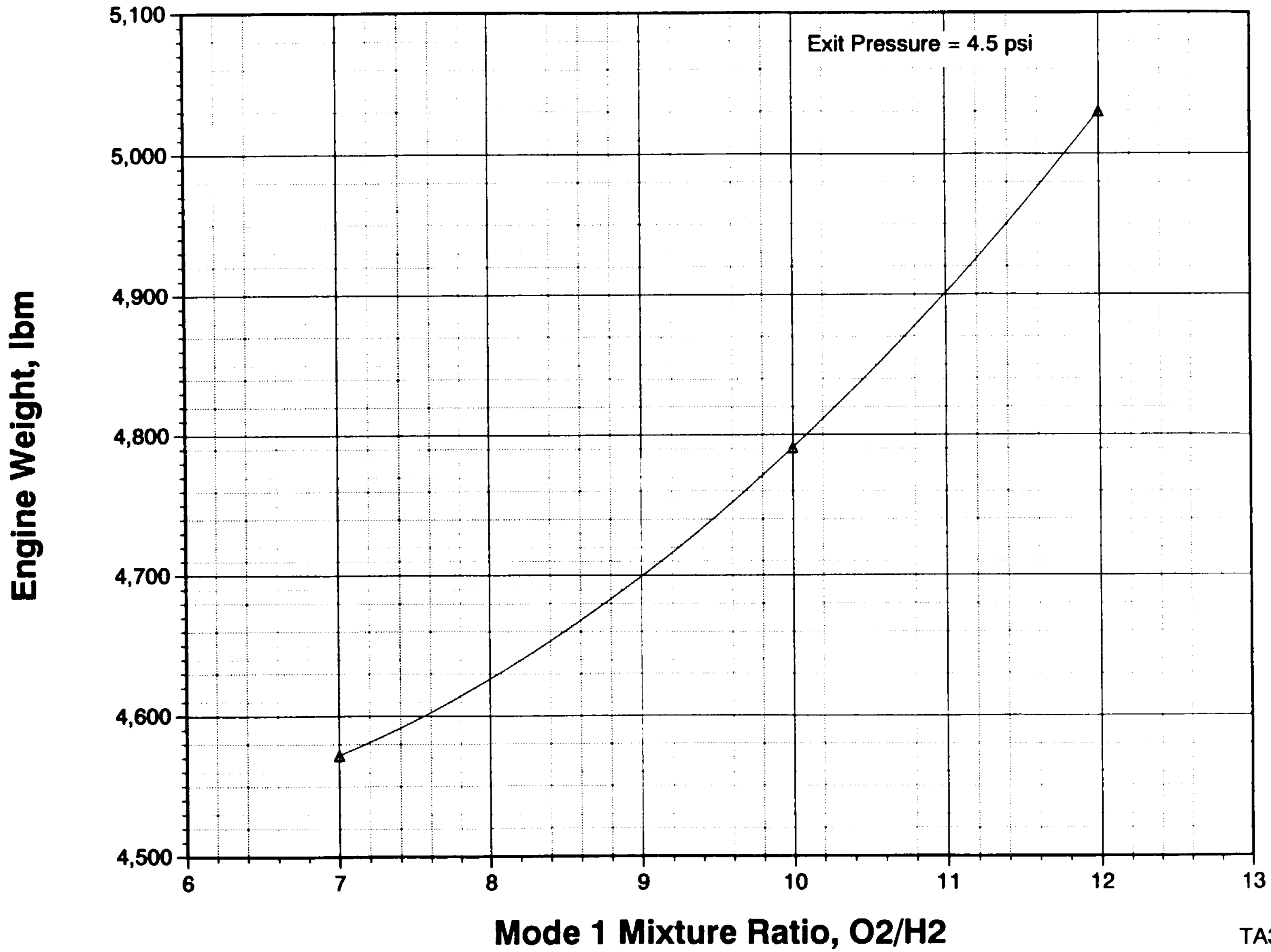
TA3–0972

SSTO Performance – Bipropellant FFSCC Engine Mixture Ratio Variation



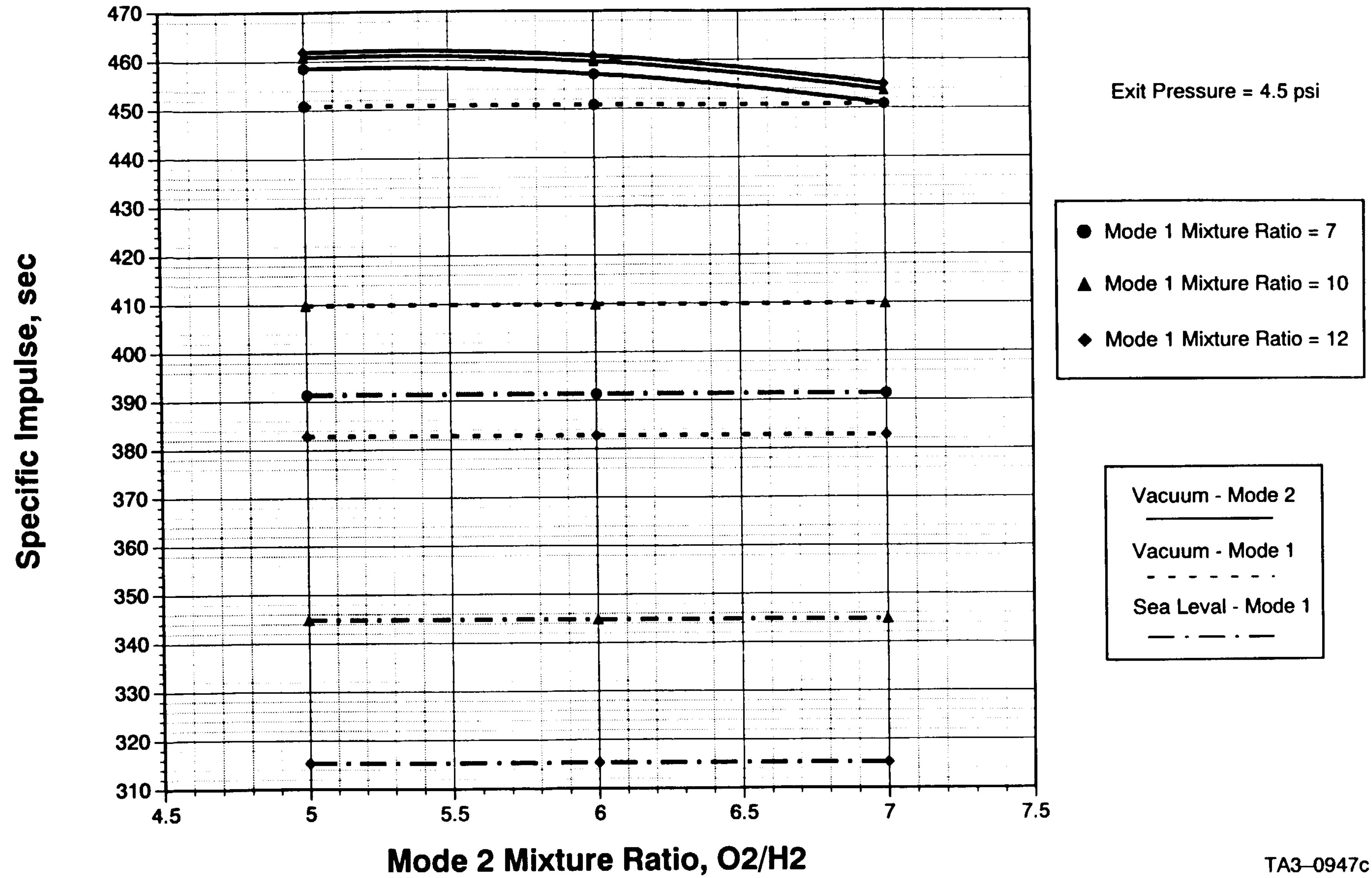
TA3–0971

Engine Weights – FFSCC
Bipropellant - Dual Mixture Ratio

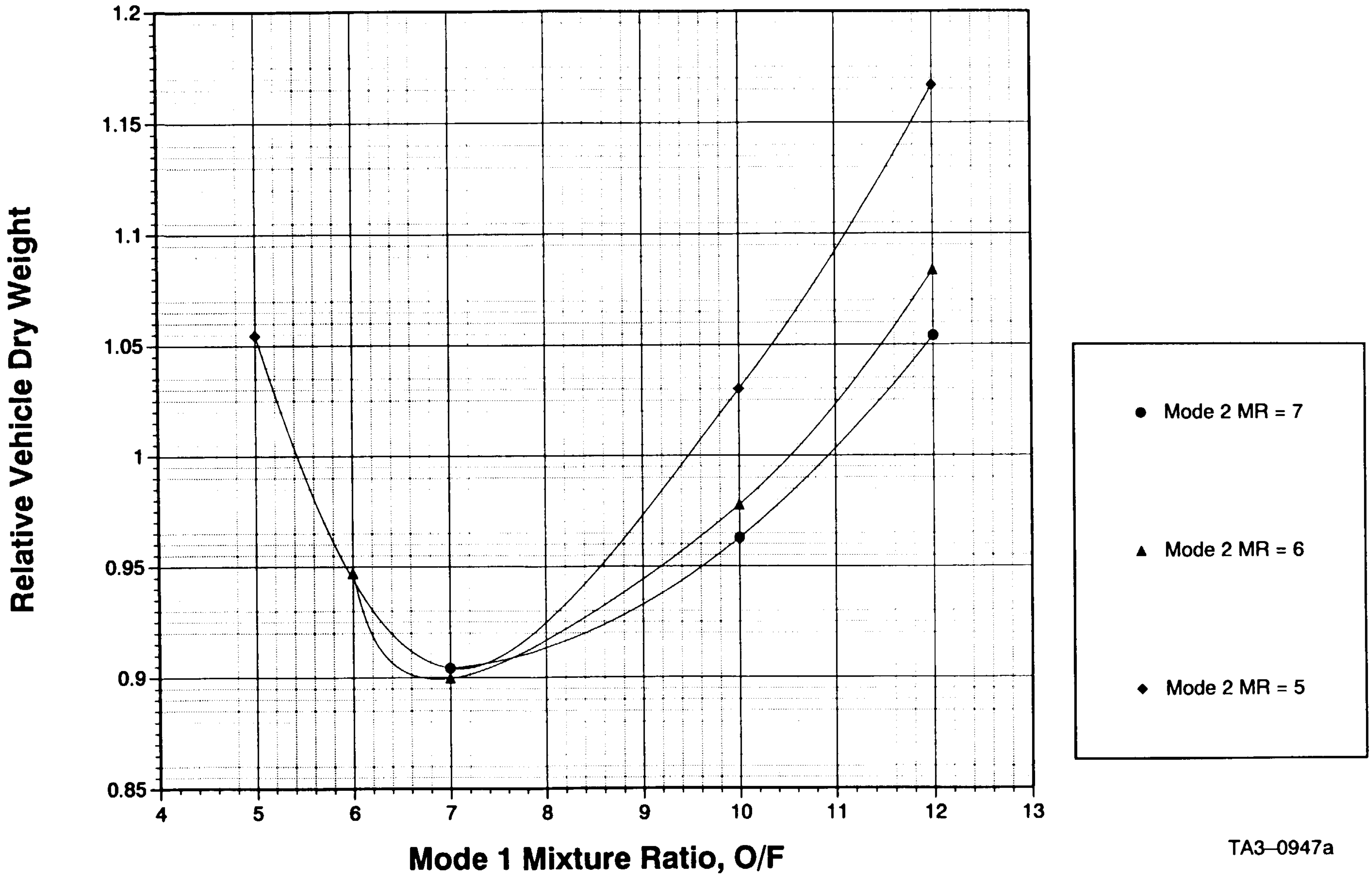


TA3–0947b

Engine Performance – FFSCC
Bipropellant - Dual Mixture Ratio Operation

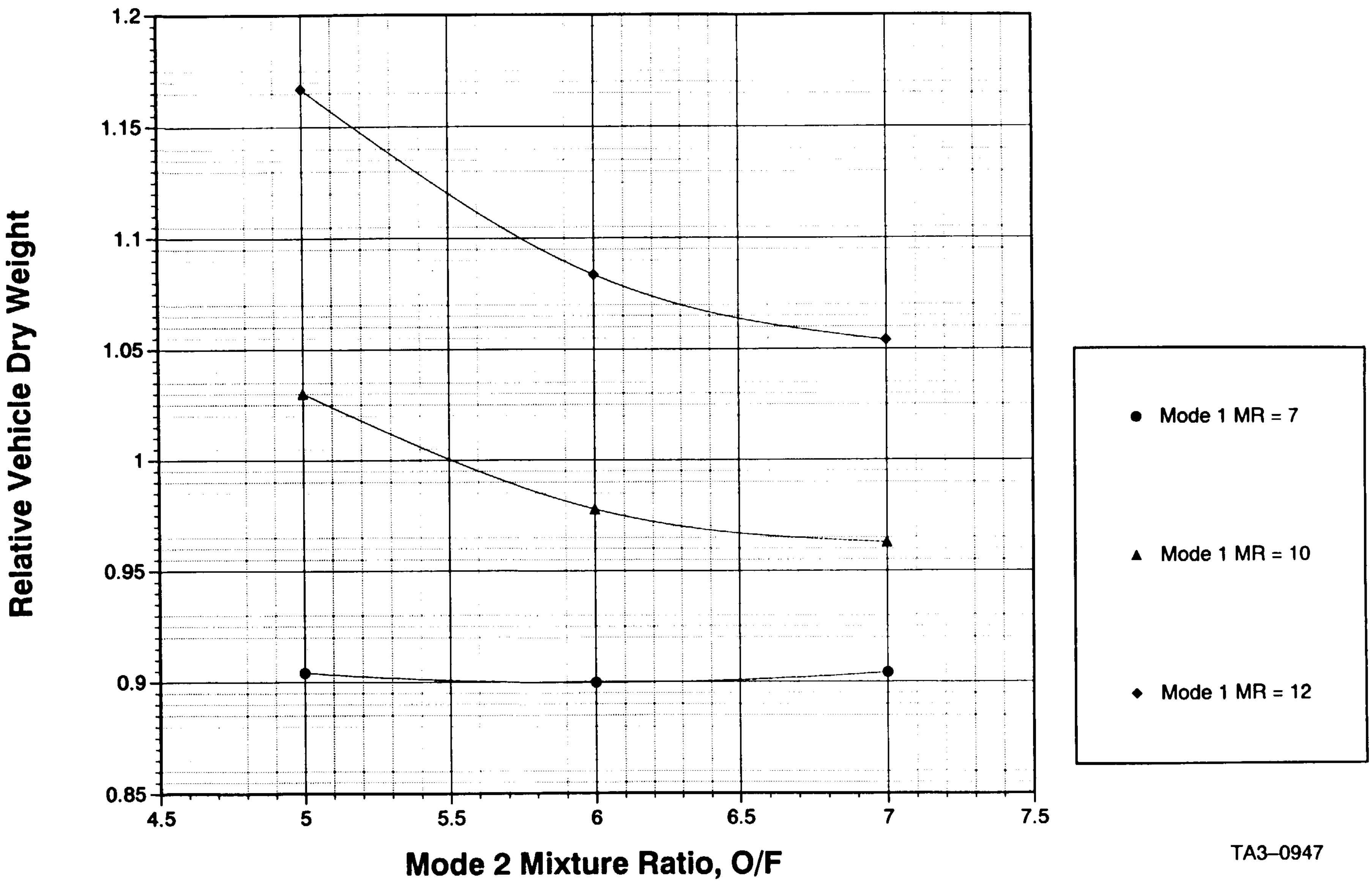


SSTO Performance – Bipropellant FFSCC
Dual Mixture Ratio Operation



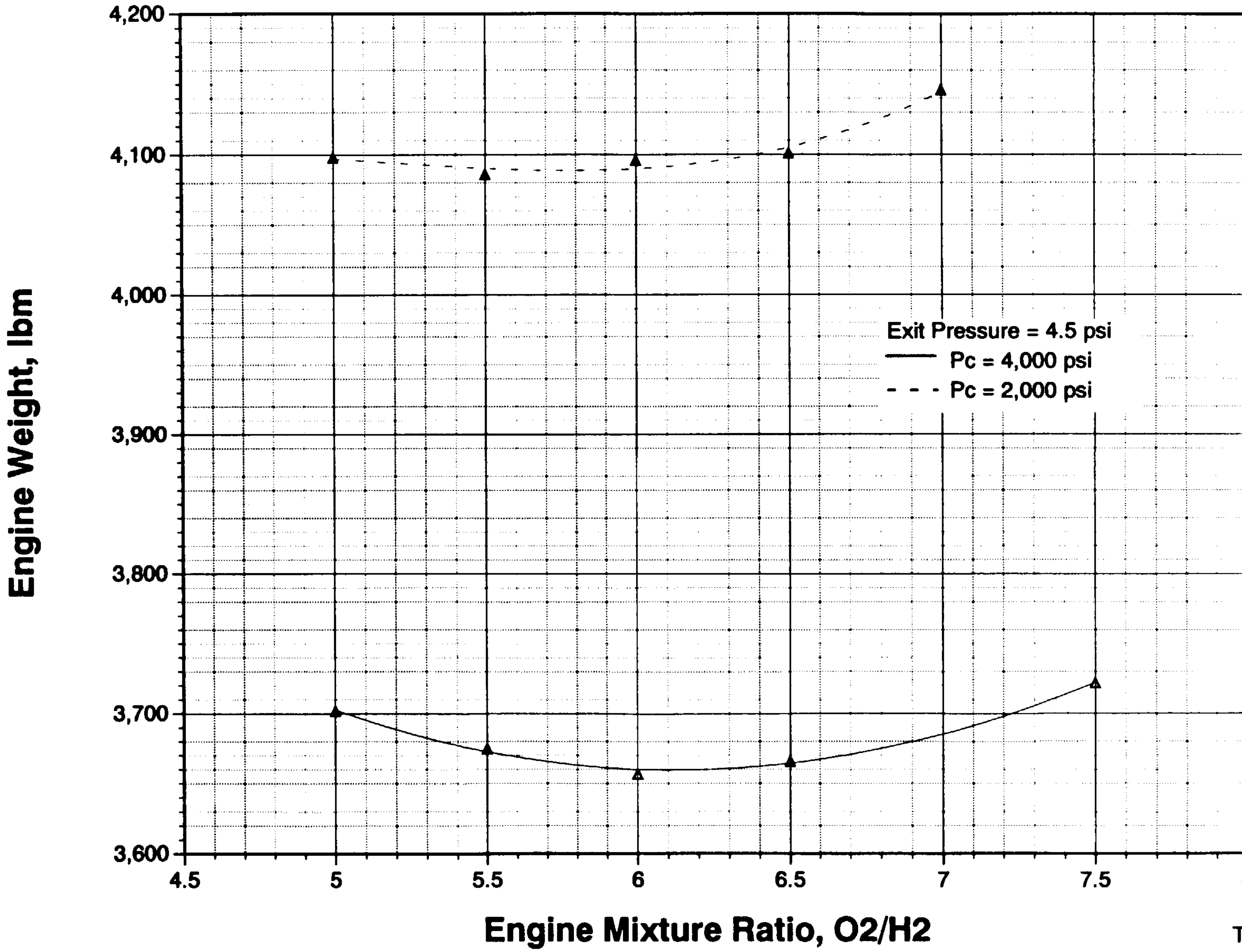
TA3–0947a

SSTO Performance – Bipropellant FFSCC
Dual Mixture Ratio Operation



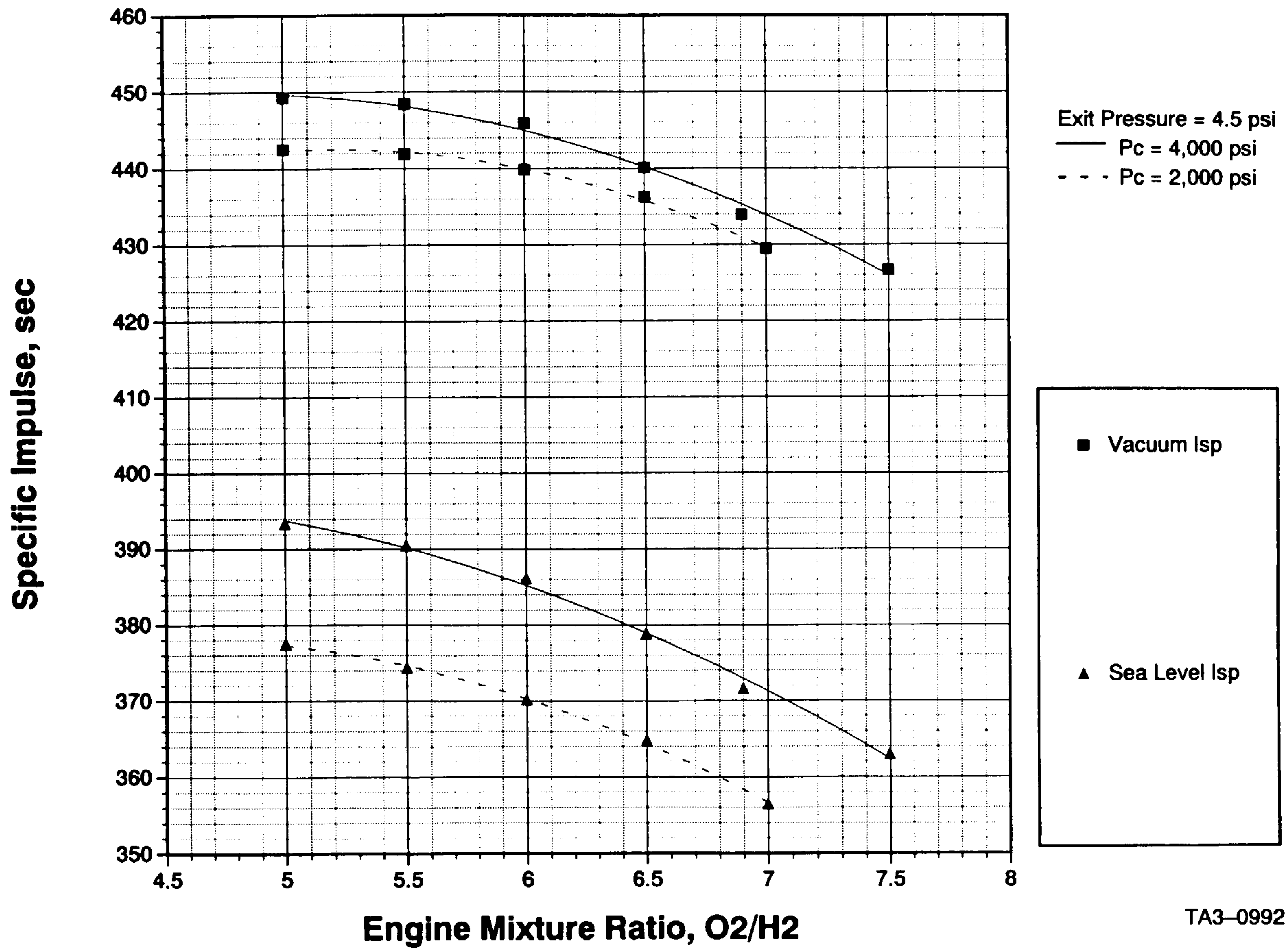
TA3–0947

Engine Weights – GG Cycle Bipropellant



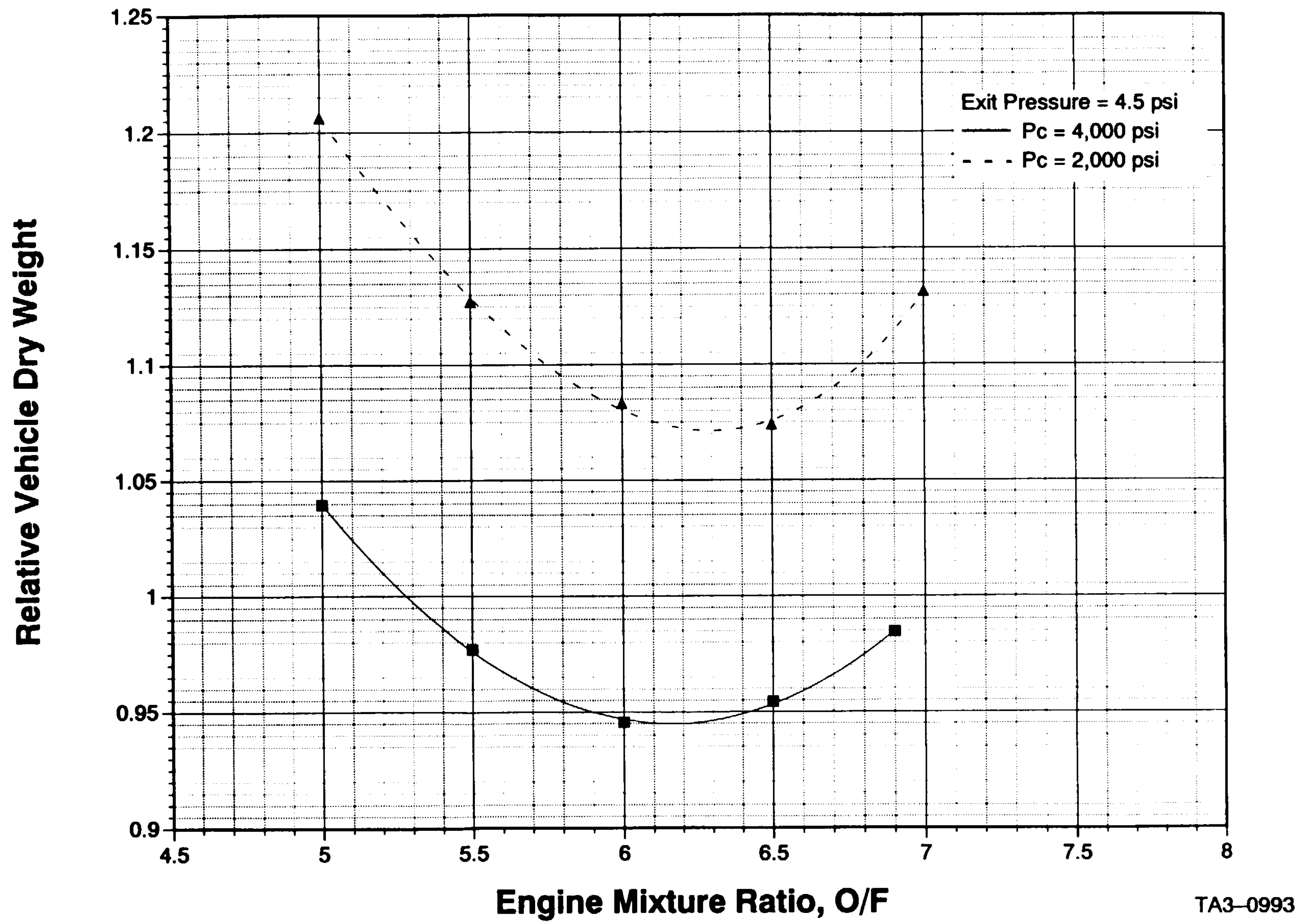
TA3–0991a

Engine Performance – GG Cycle
Bipropellant



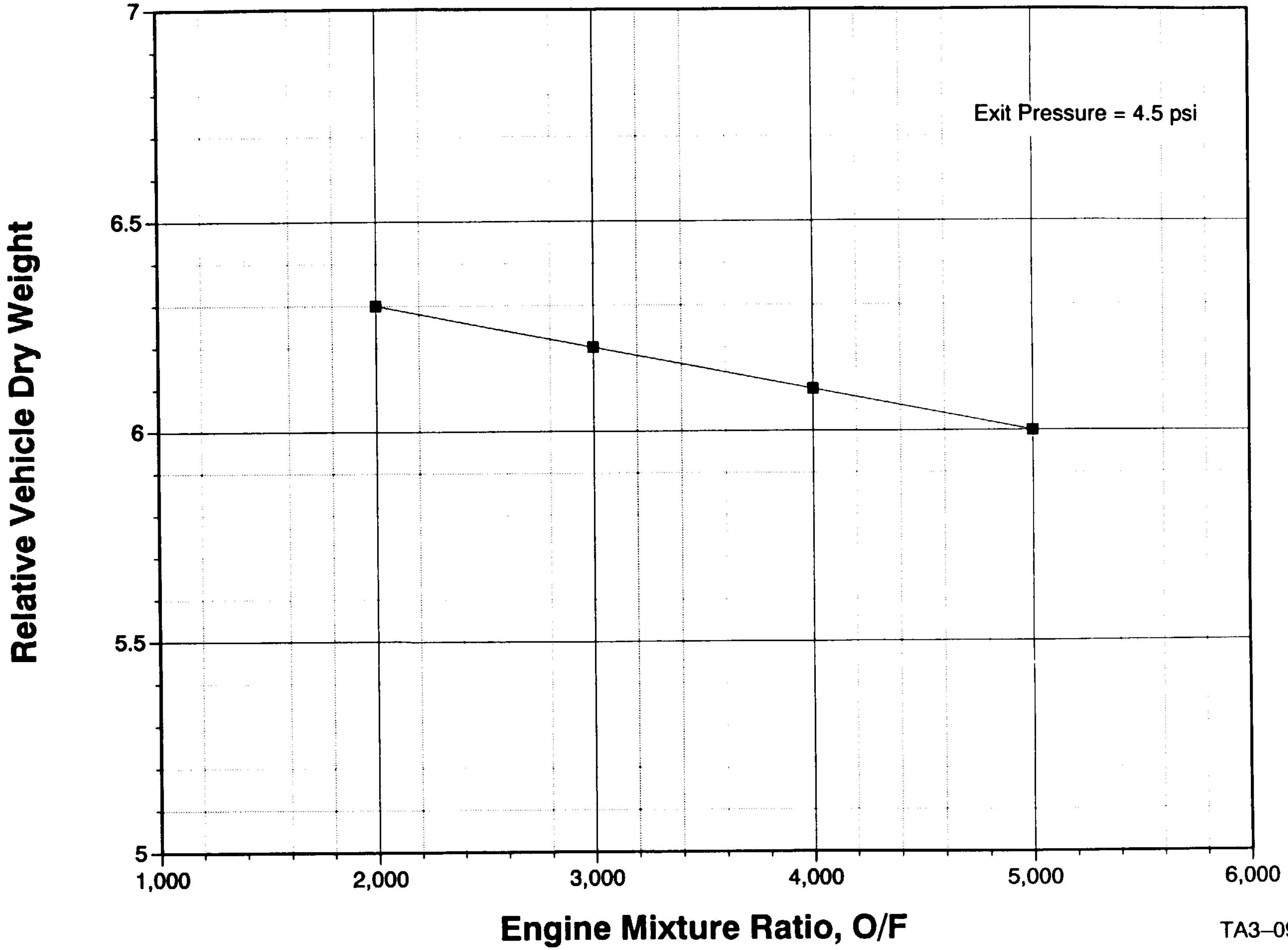
TA3–0992

SSTO Performance – Bipropellant GG Cycle
Engine Mixture Ratio Variation



TA3–0993

SSTO Performance – Bipropellant GG Cycle
Optimum Engine Mixture Ratio

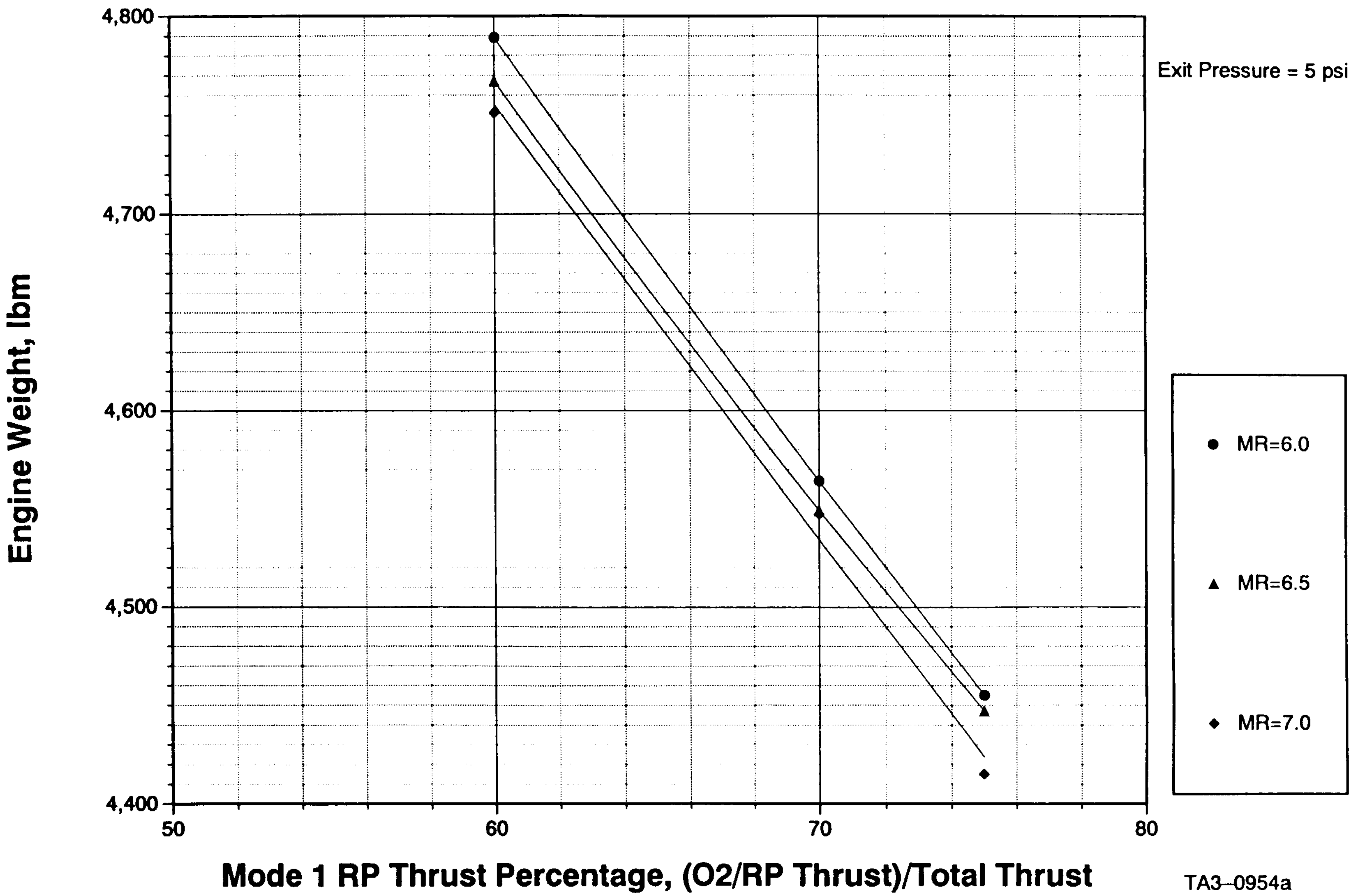


TA3–0993a

Bell Annular Thrust Split

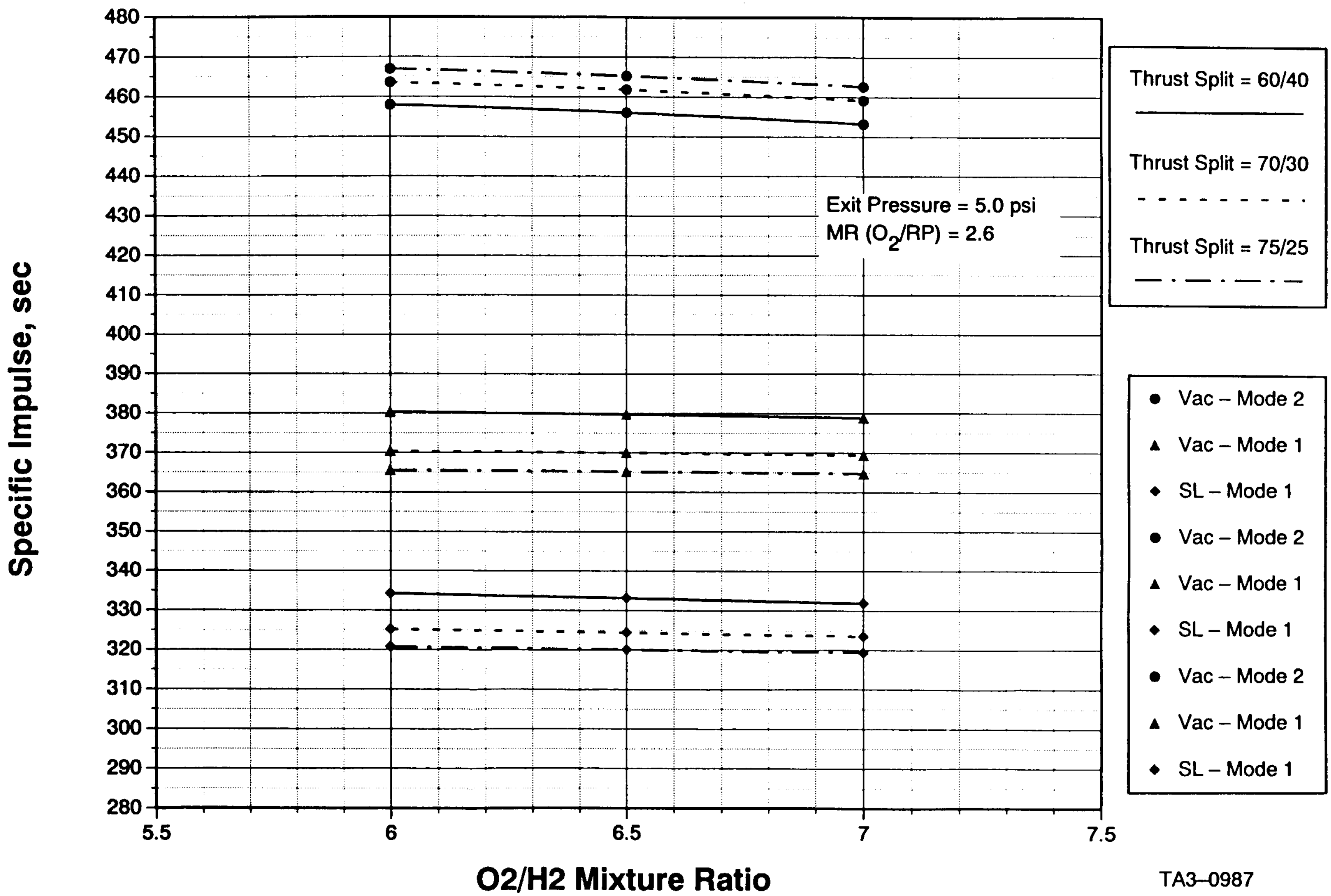
TA3–0863h

Engine Weights – FFSCC
Bell Annular Configuration



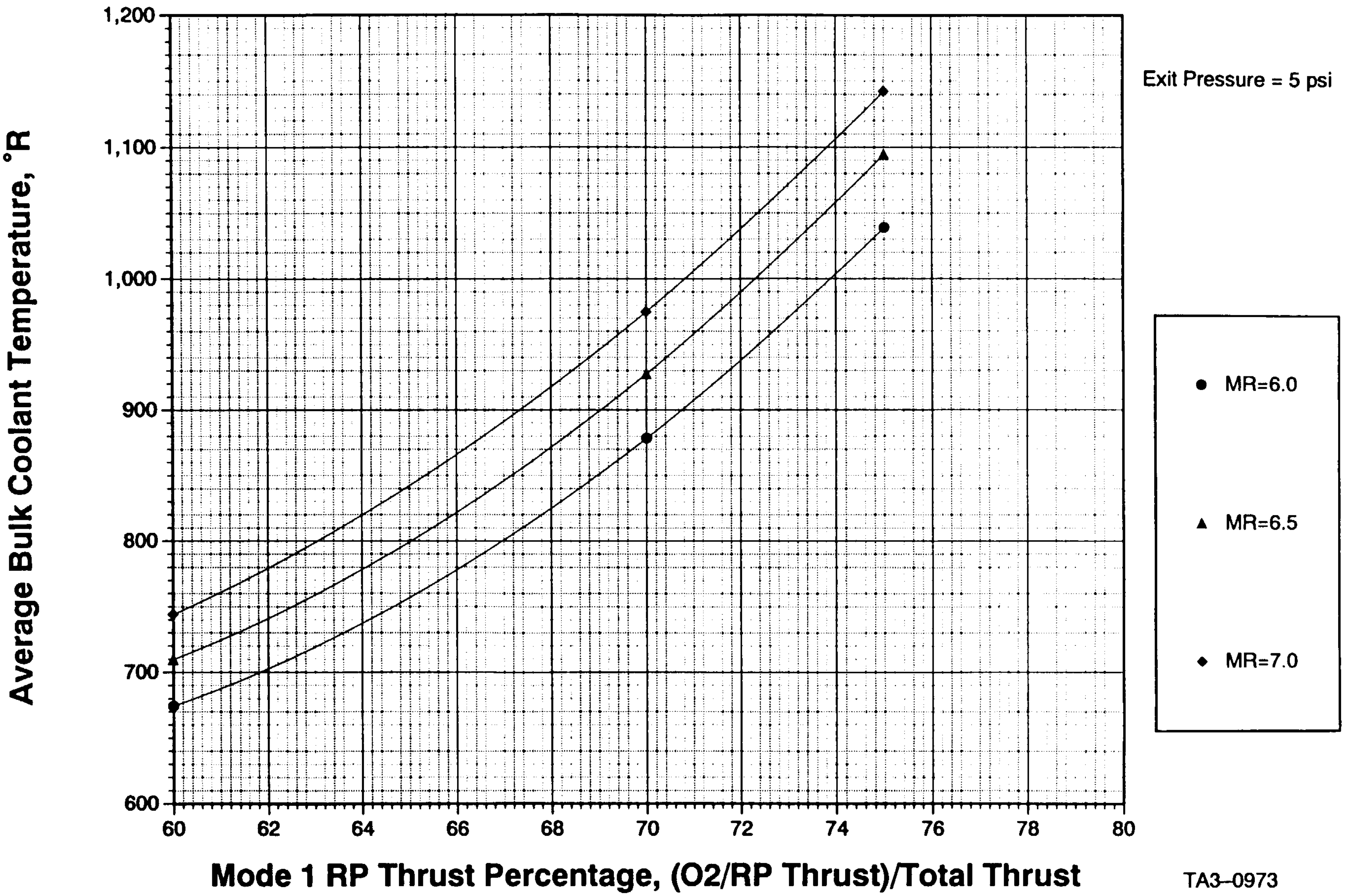
TA3–0954a

Specific Impulse – FFSCC
Bell Annular Configuration



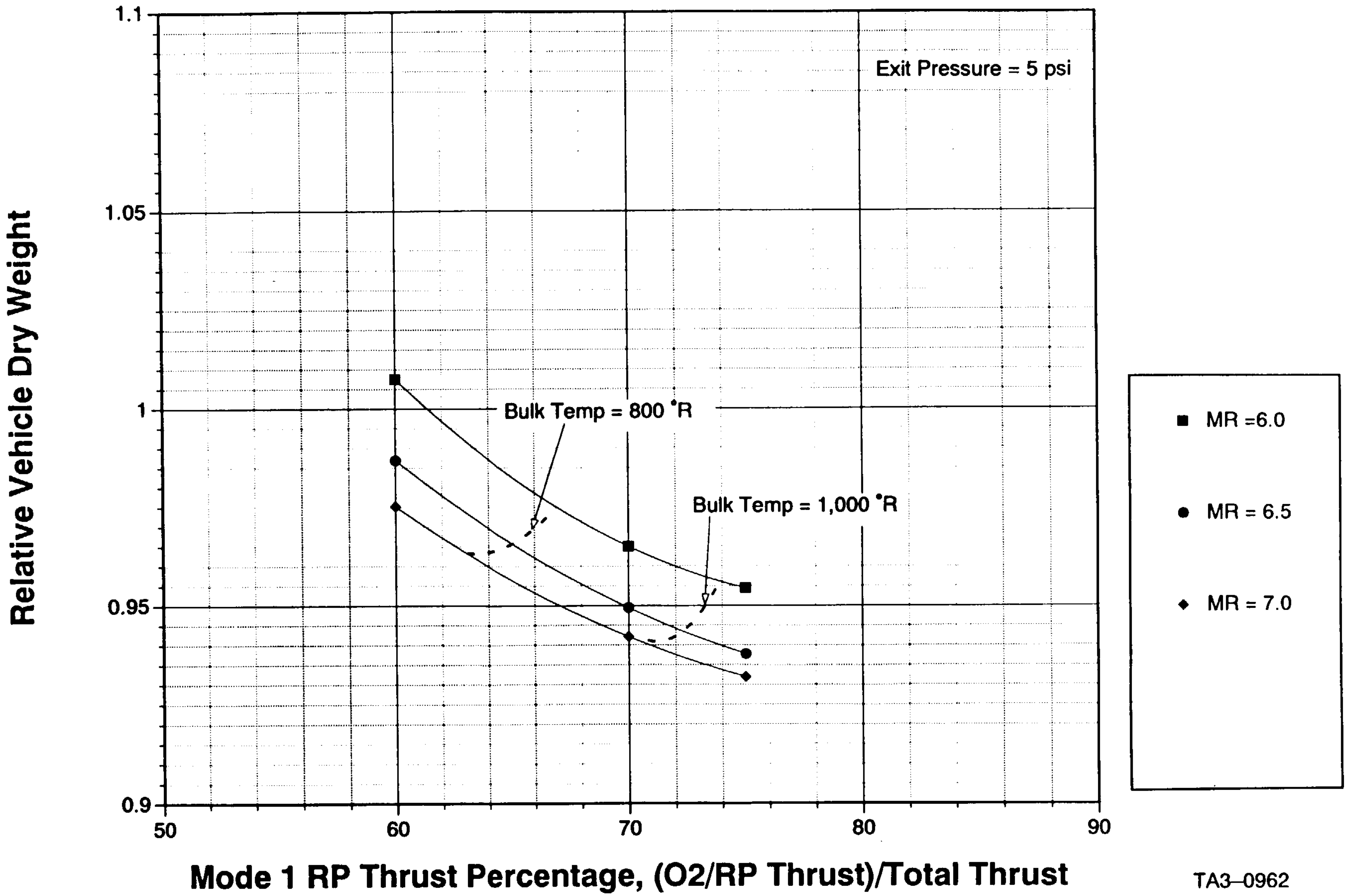
TA3–0987

Coolant Temperature – Tripropellant – FFSCC
Bell Annular Configuration



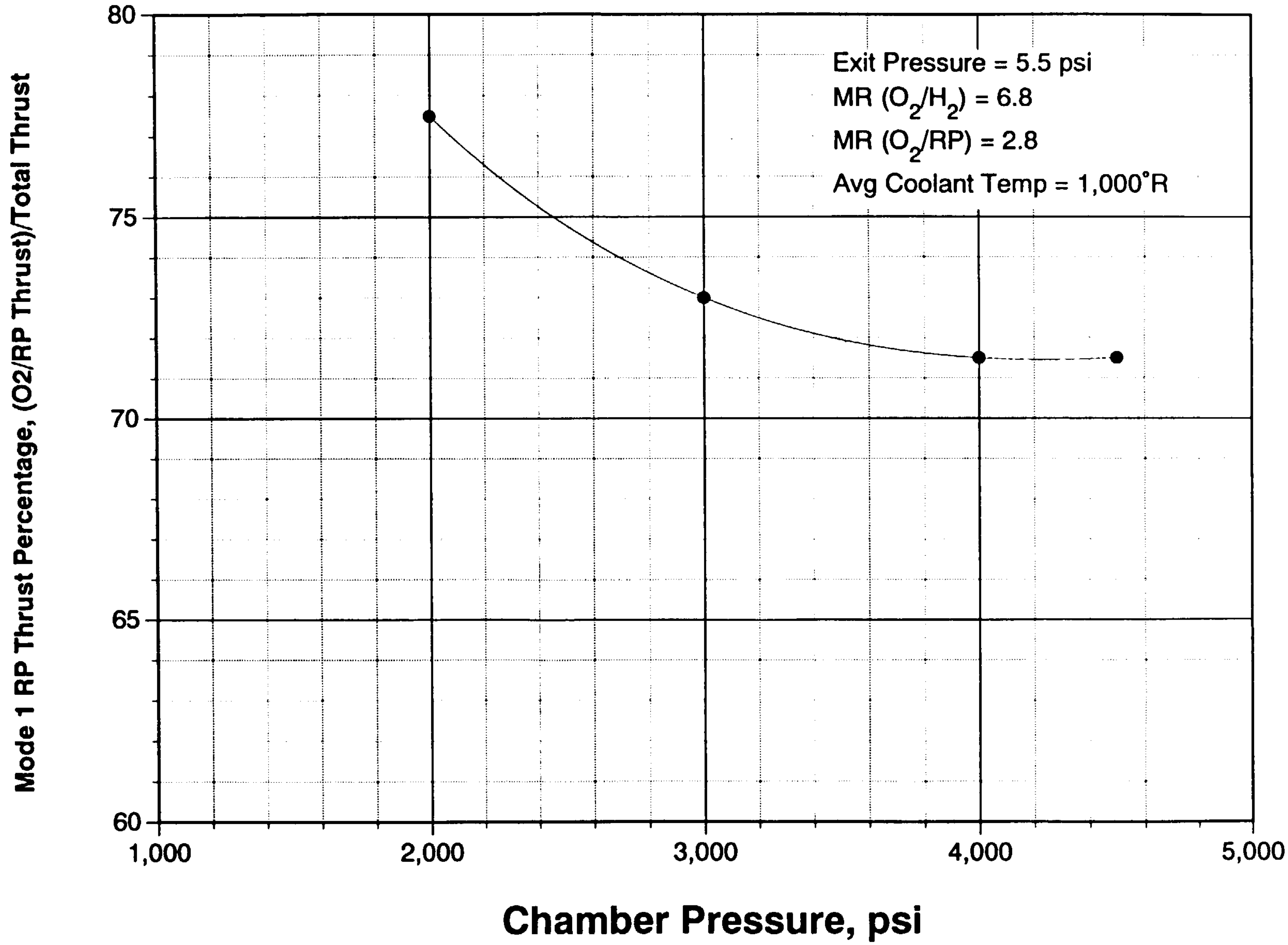
TA3–0973

SSTO Performance – Tripropellant – FFSCC
Bell Annular Configuration



TA3–0962

Thrust Split Vs Chamber Pressure
Bell Annular Configuration

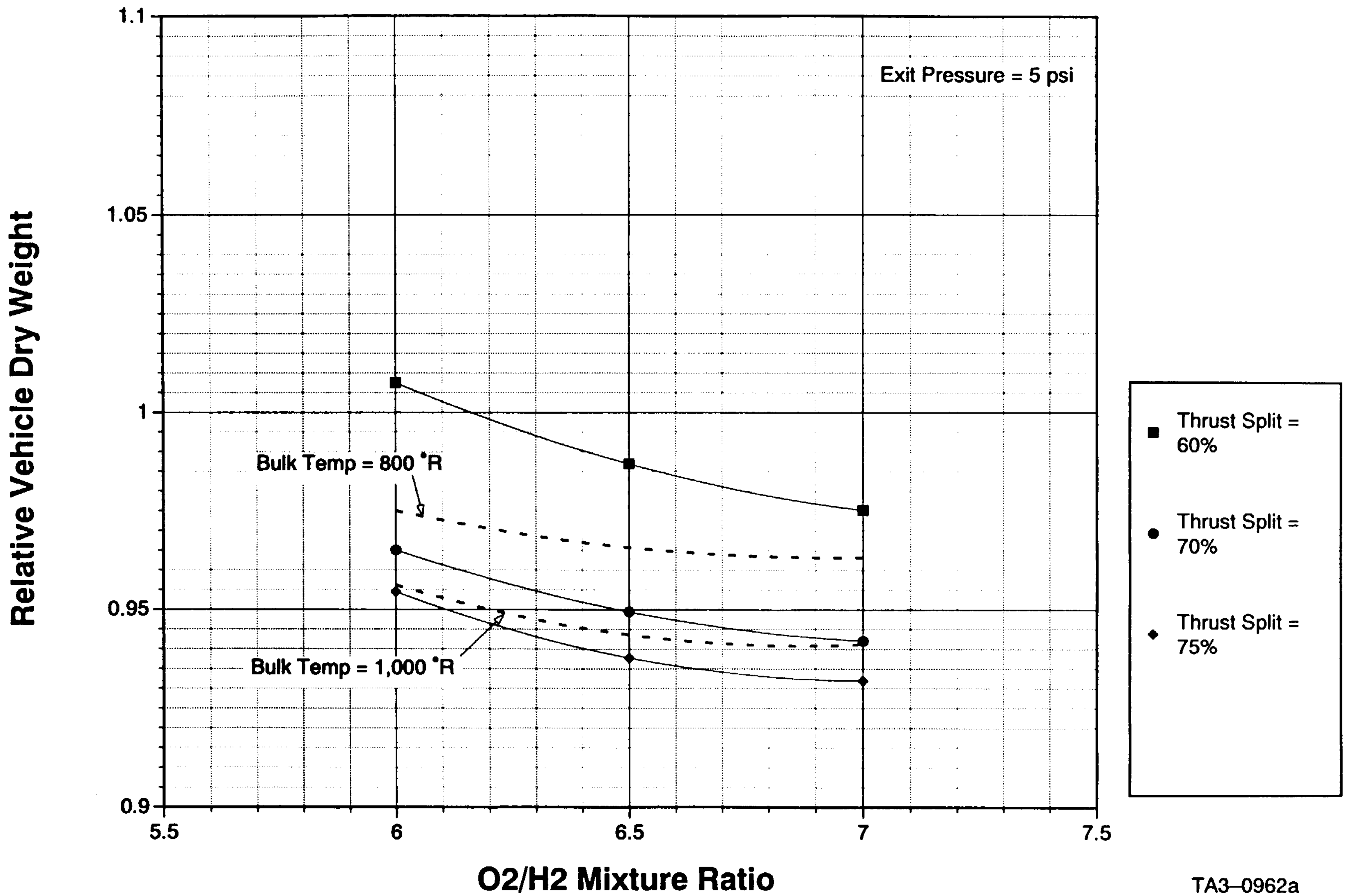


TA3–0954b

Bell Annular Mode 2 Mixture Ratio

TA3–0863j

SSTO Performance – Tripropellant – FFSCC
Bell Annular Configuration

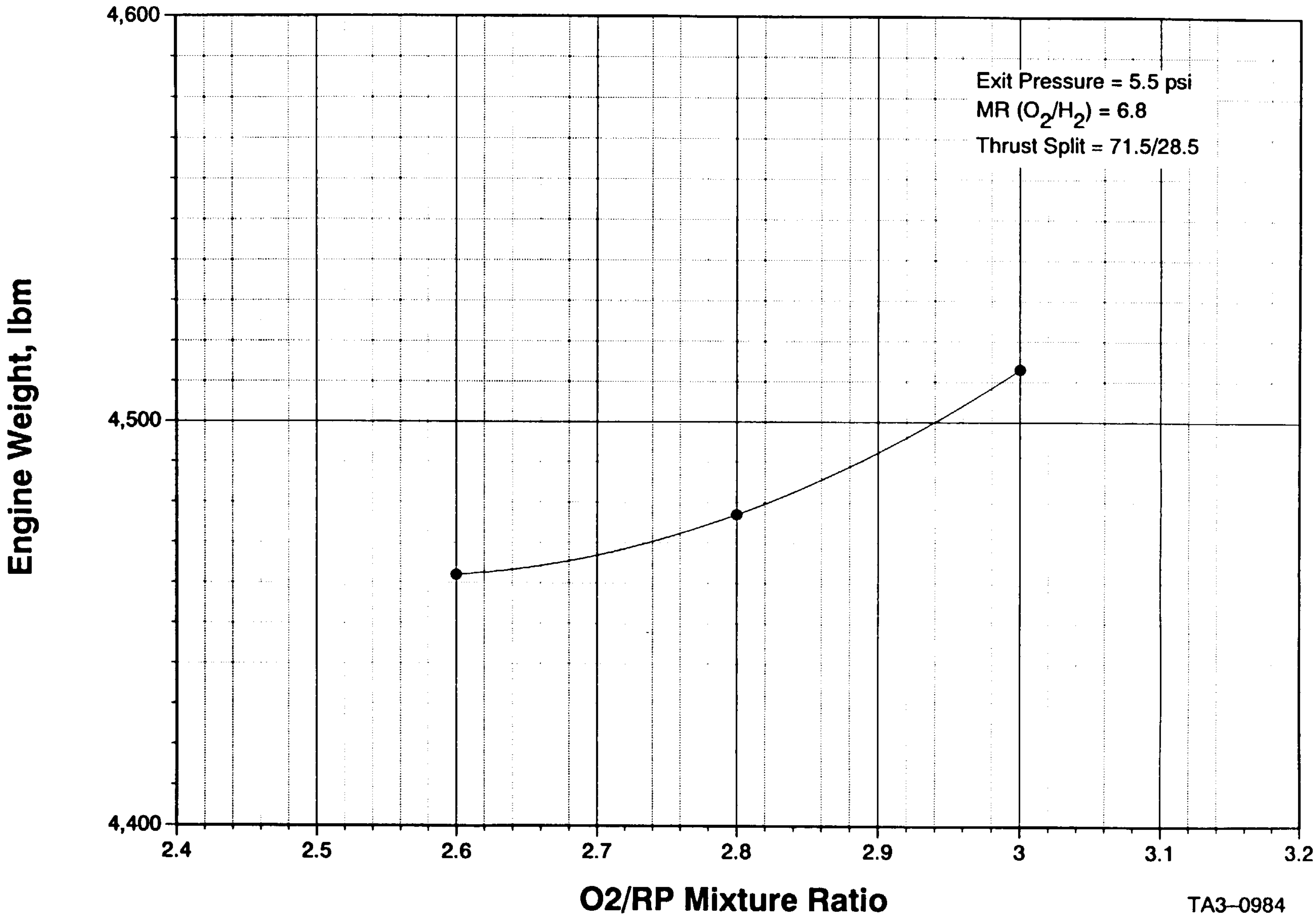


TA3–0962a

Bell Annular Mode 1 Mixture Ratio

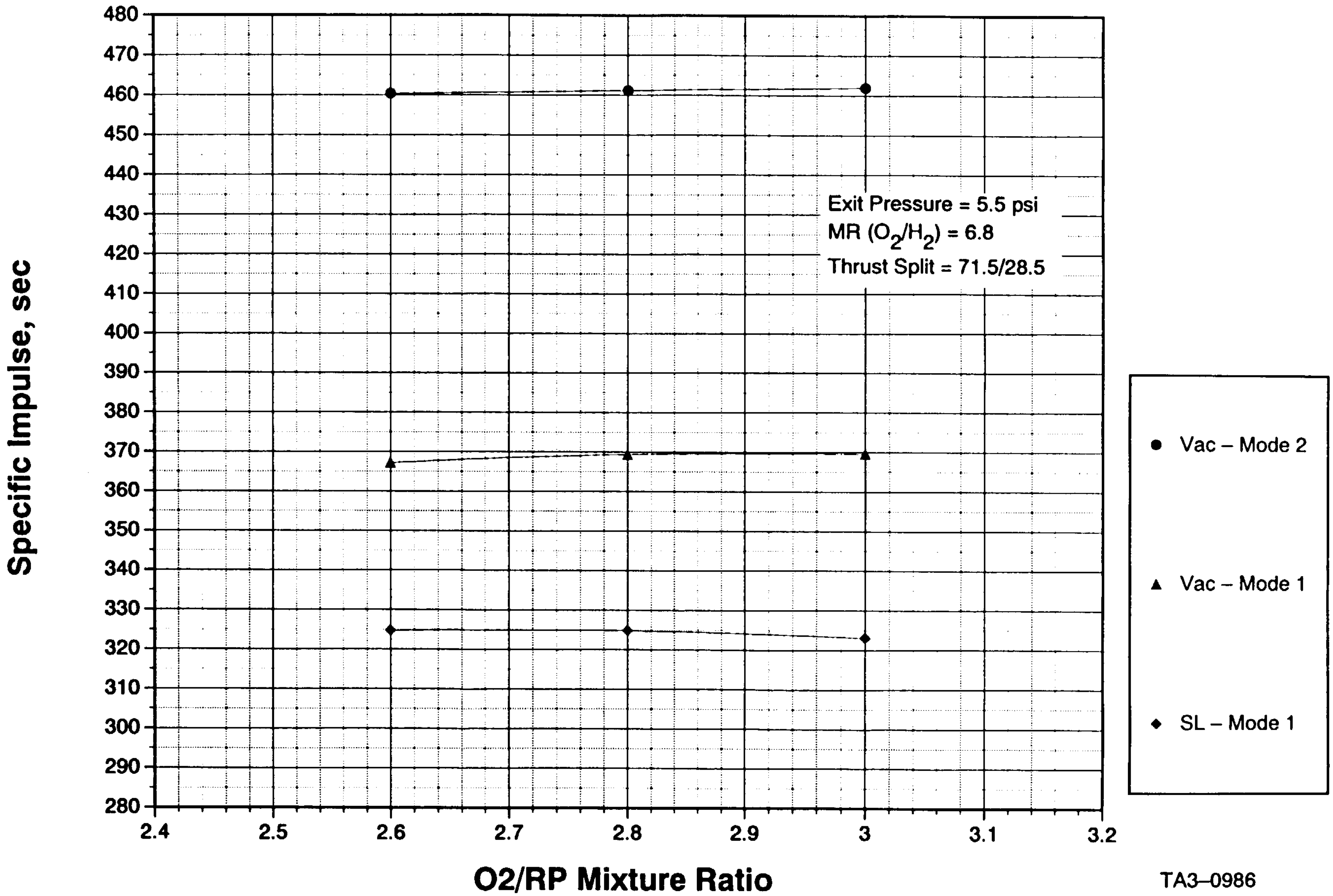
TA3–0863k

Engine Weights – FFSCC
Bell Annular Configuration



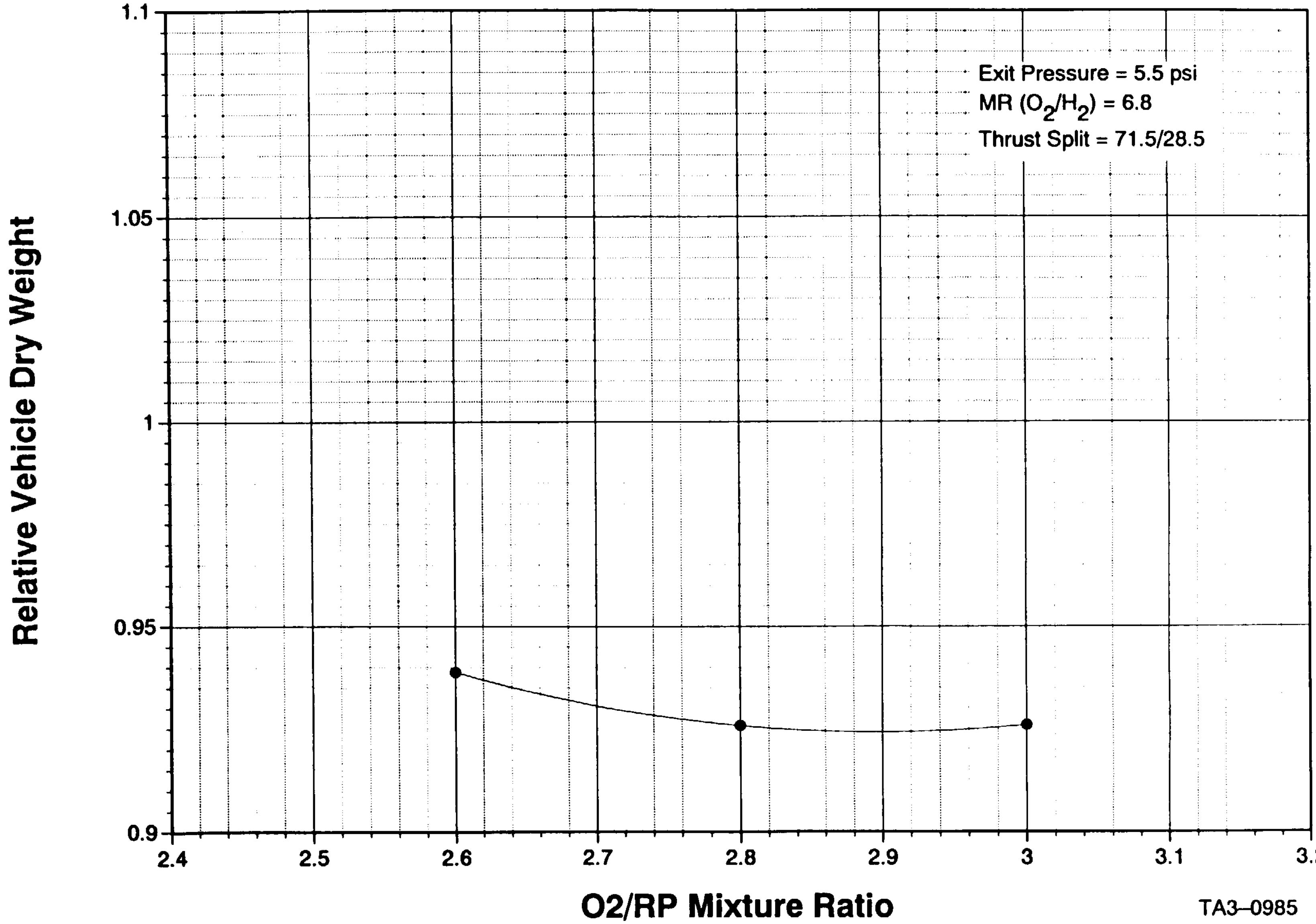
TA3–0984

Specific Impulse – FFSCC
Bell Annular Configuration



TA3–0986

SSTO Performance – FFSCC
Bell Annular Configuration



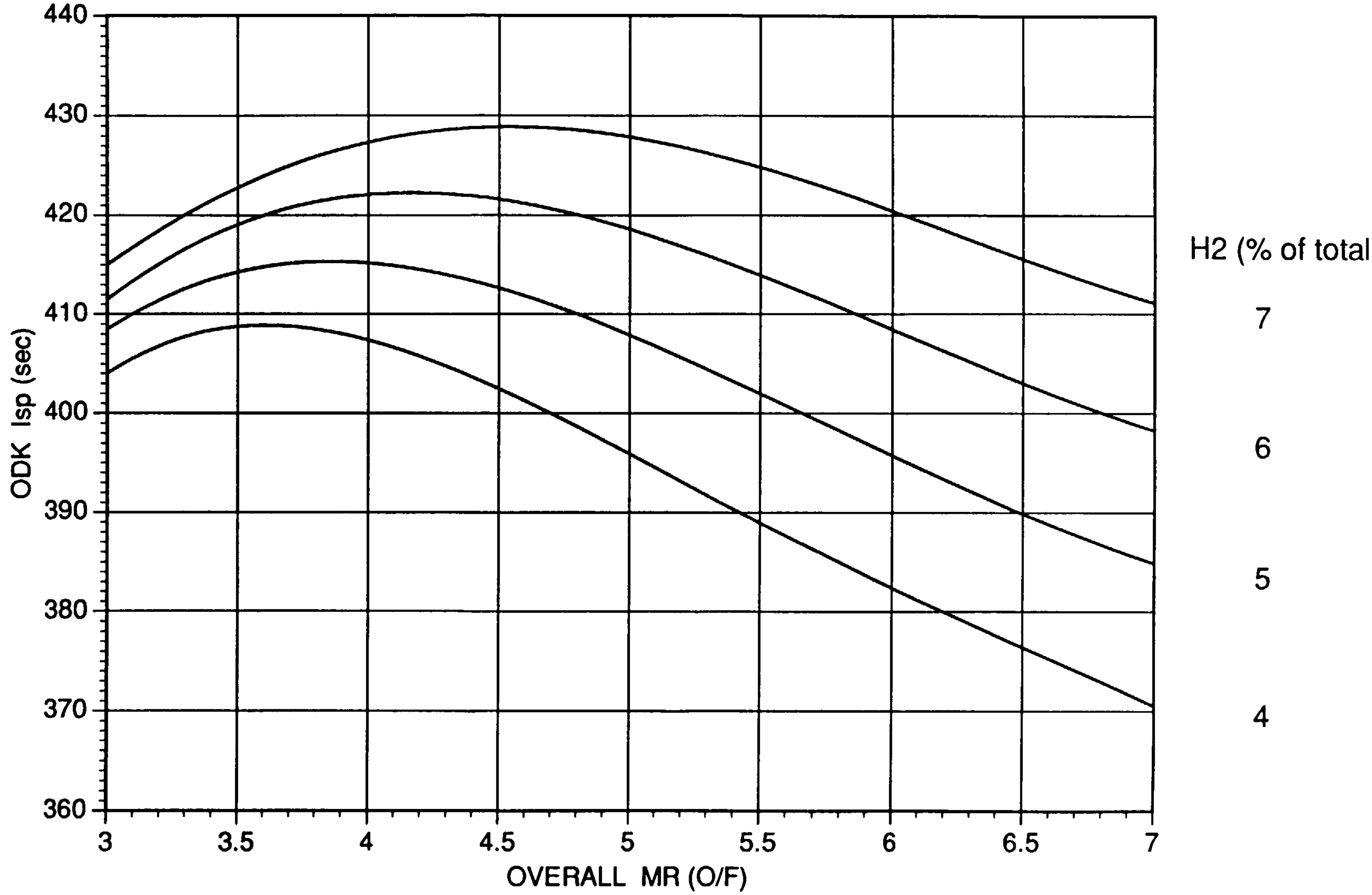
TA3–0985

Single Chamber Percent Hydrogen

TA3–0863m

O2/H2/RP ODK Performance

PC=4000 ,EPS=88,Hf=0.55,Rt=4.47

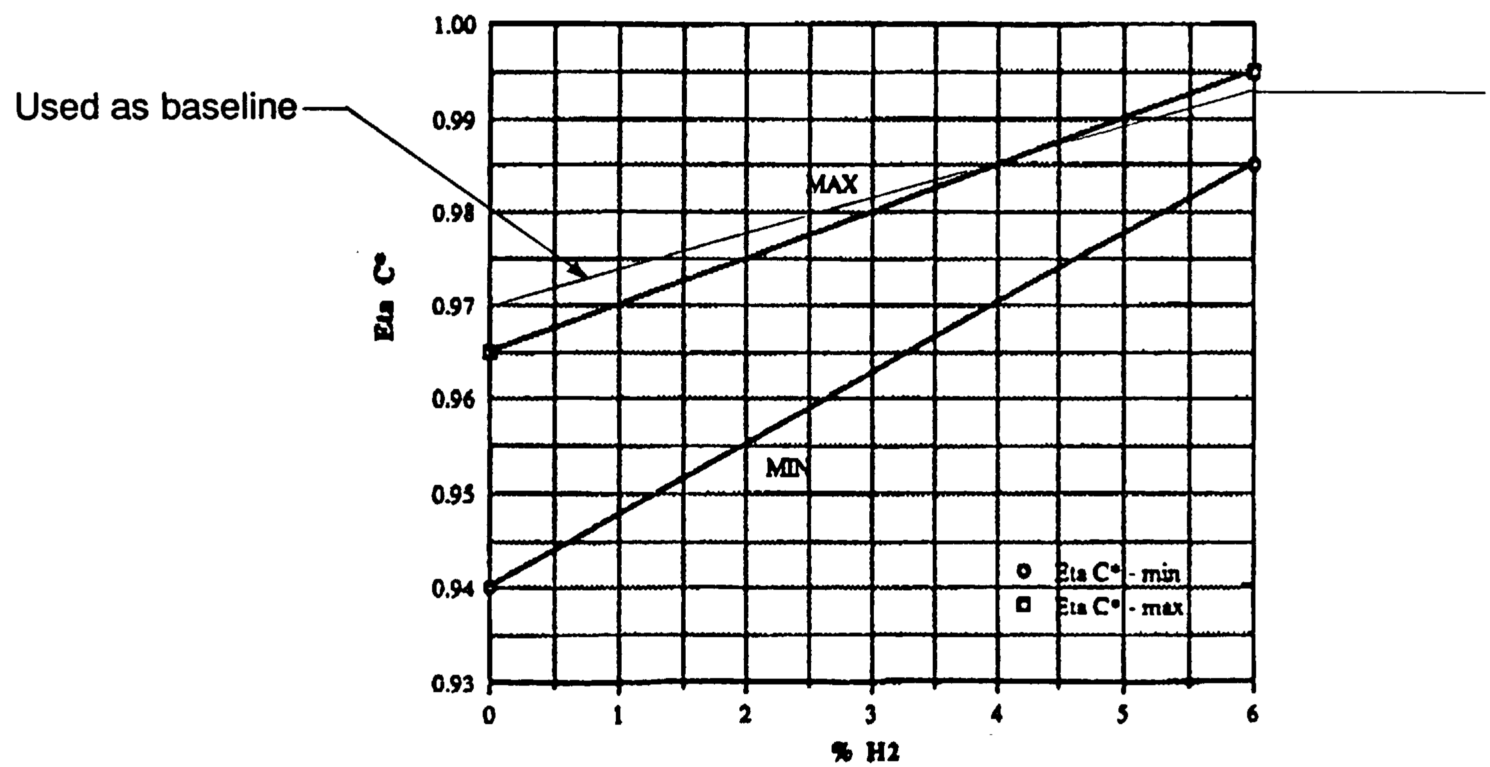


2-9-95

Energy Release Efficiency

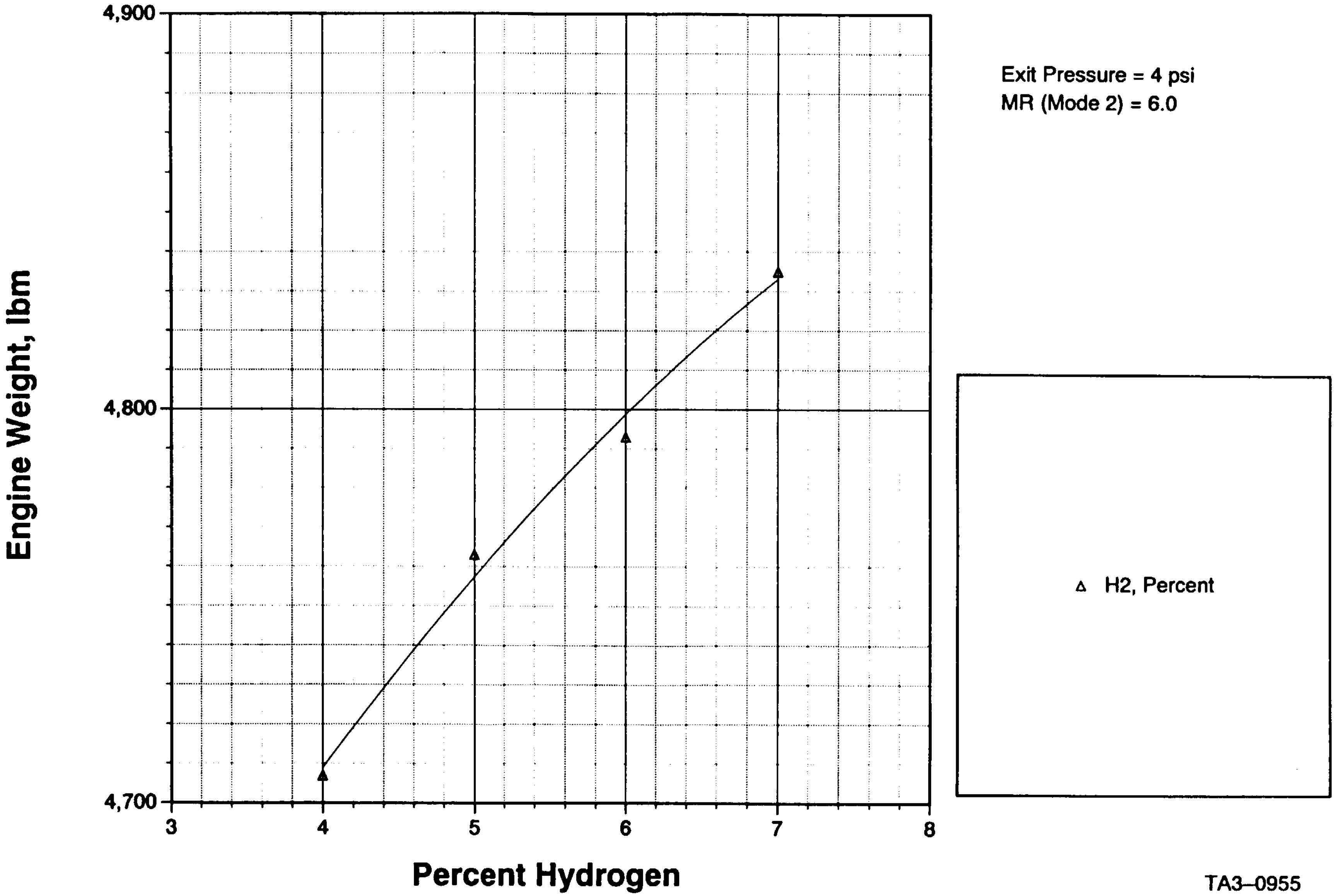
- Chart From MSFC

Eta C* Range for Rocketdyne Study
Dual Mode Tripropellant Injectors



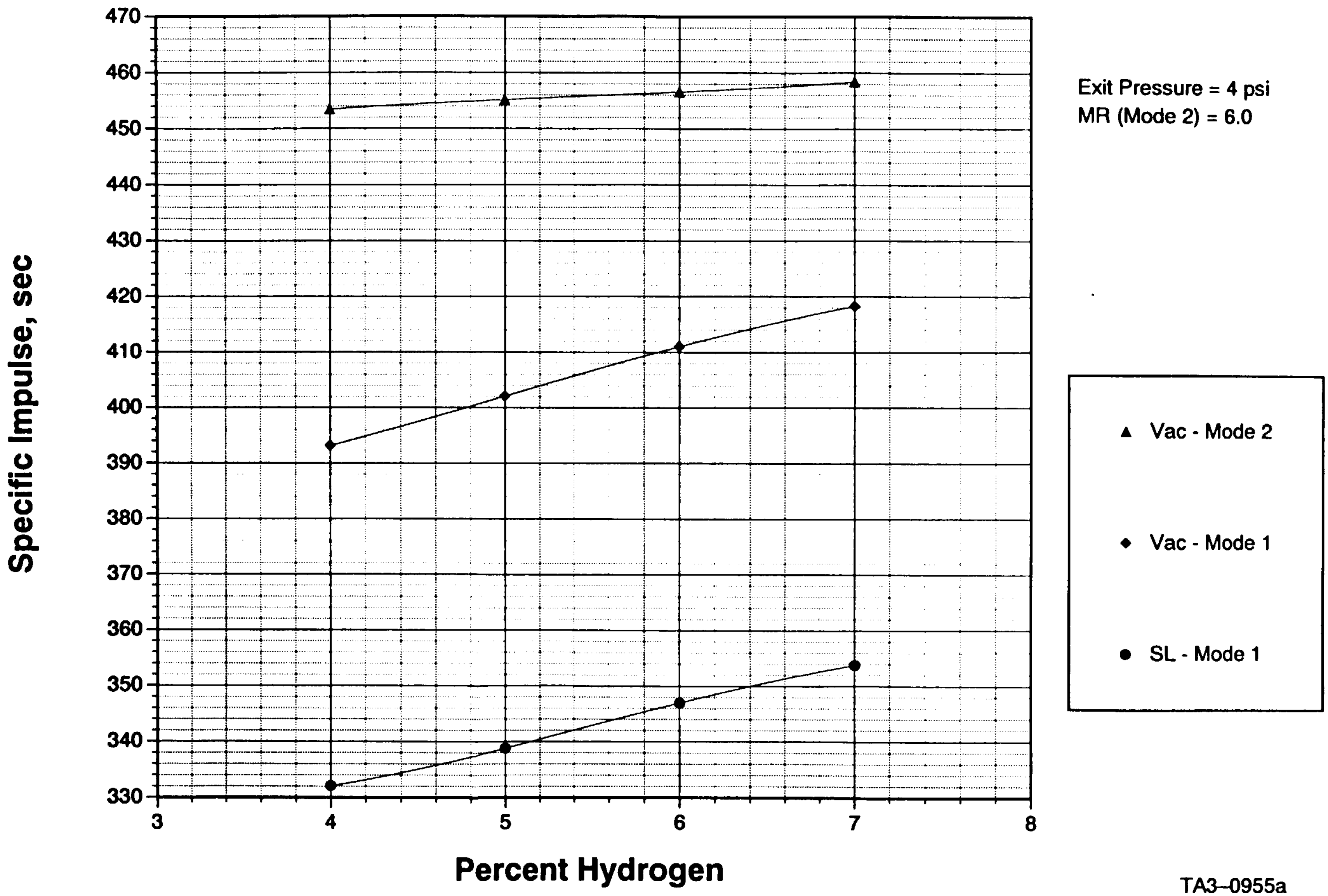
TA3–0855

Engine Weights – FFSCC
Tripropellant – Single Chamber



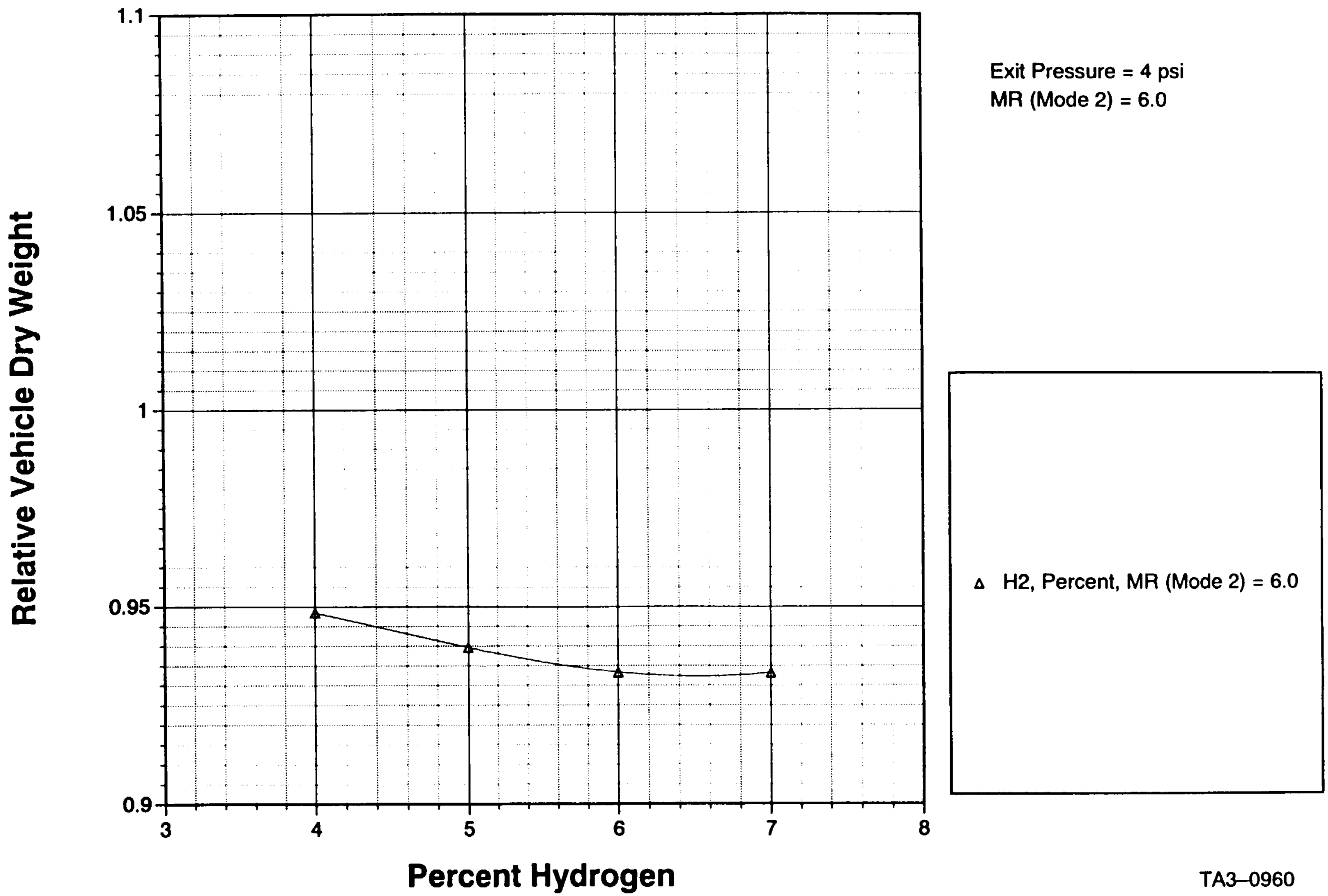
TA3–0955

Engine Performance – FFSCC
Tripropellant Single Chamber



TA3–0955a

SSTO Performance – FFSCC
Tripropellant Single Chamber

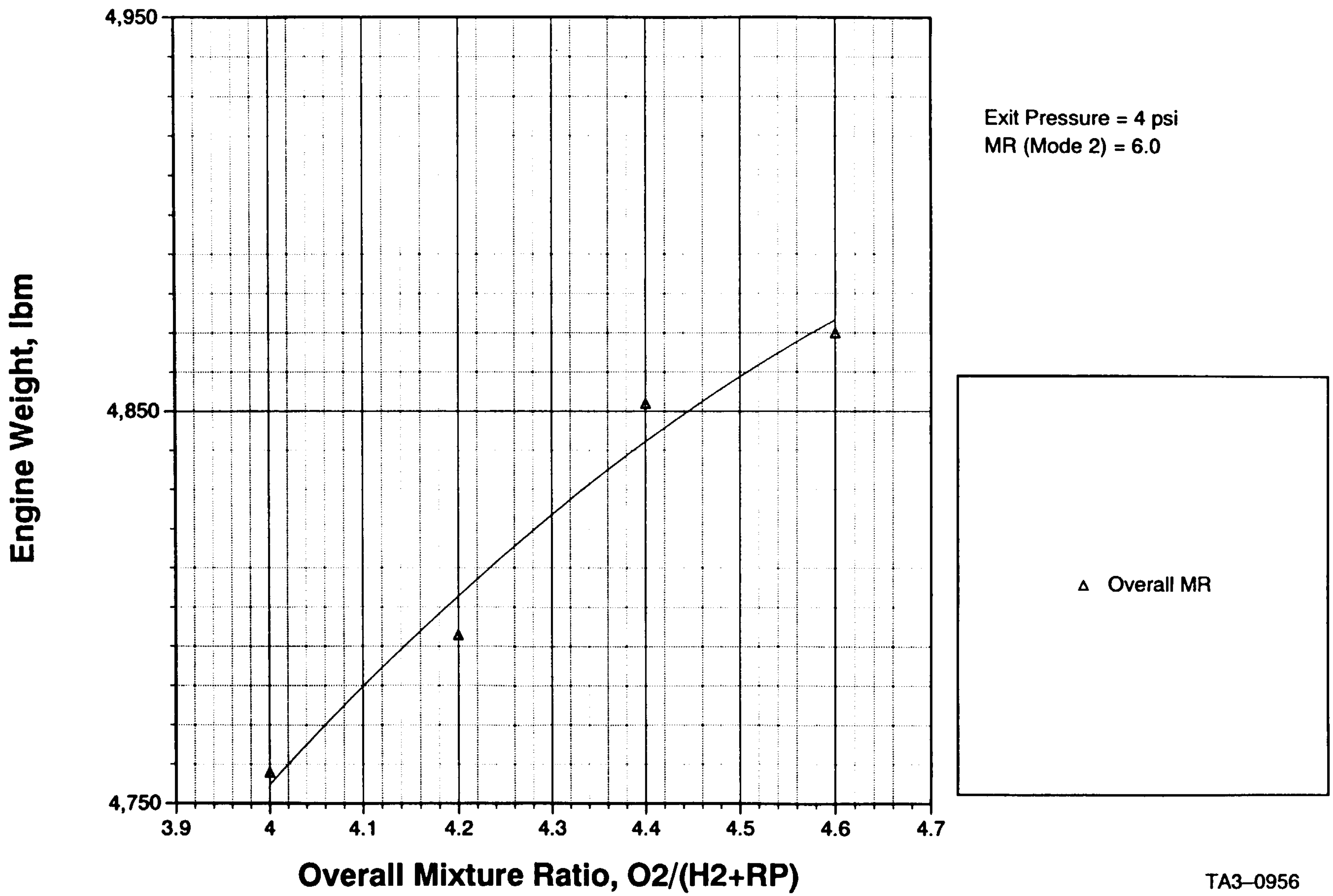


TA3–0960

Single Chamber Mode 1 Mixture Ratio

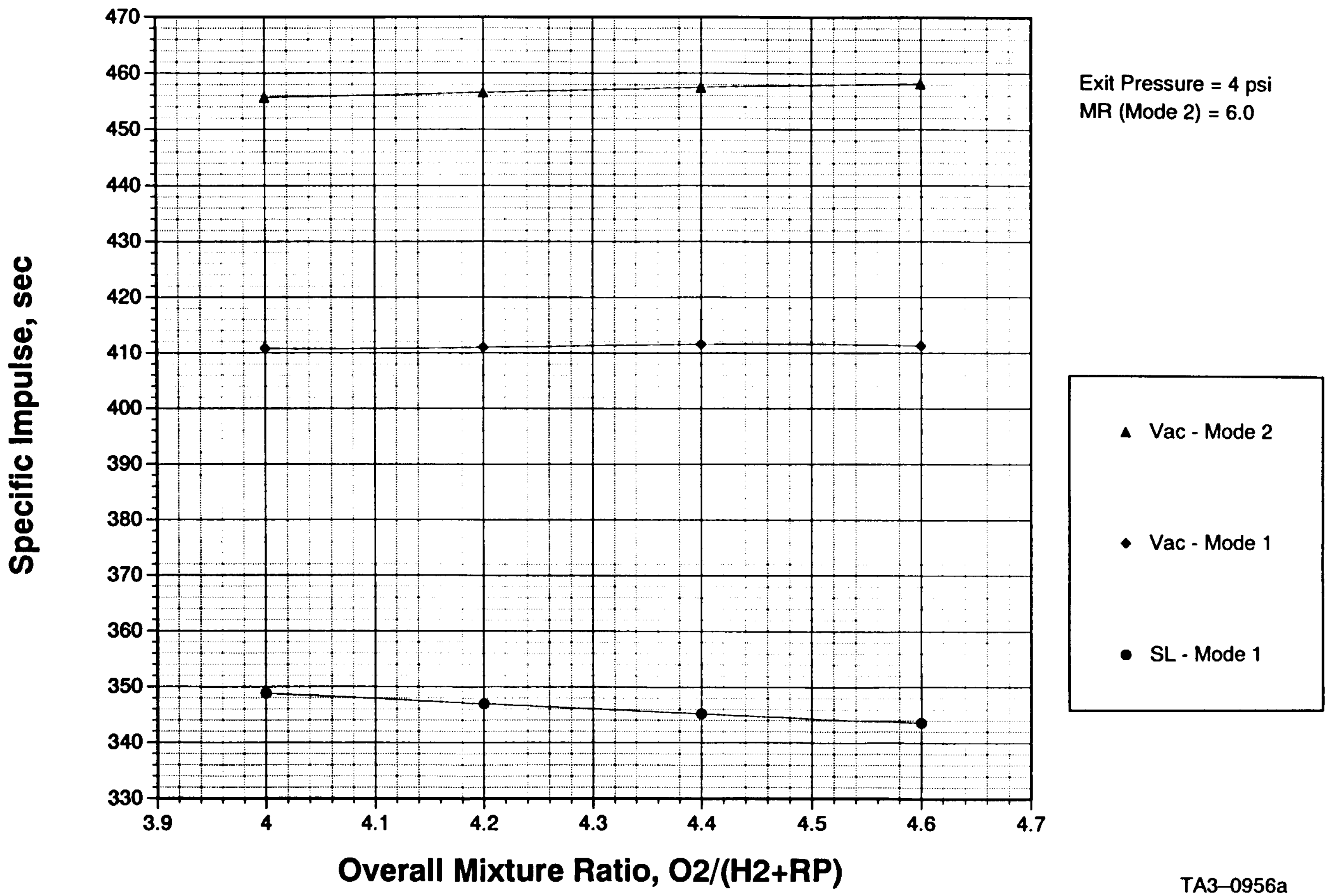
TA3–0863n

Engine Weights – FFSCC
Tripropellant Single Chamber



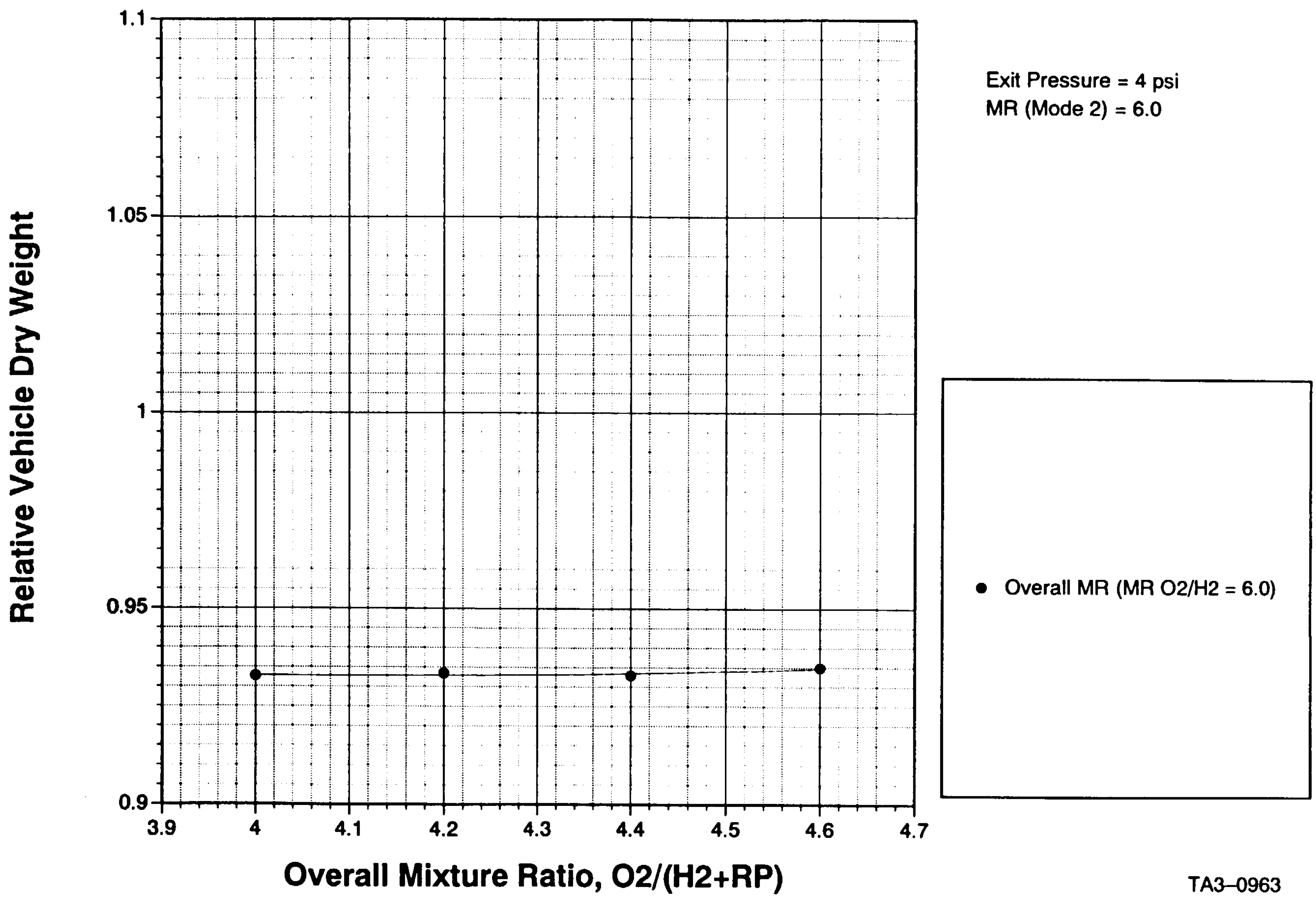
TA3–0956

Engine Performance – FFSCC
Tripropellant Single Chamber



TA3–0956a

SSTO Performance
Tripropellant Single Chamber – FFSCC

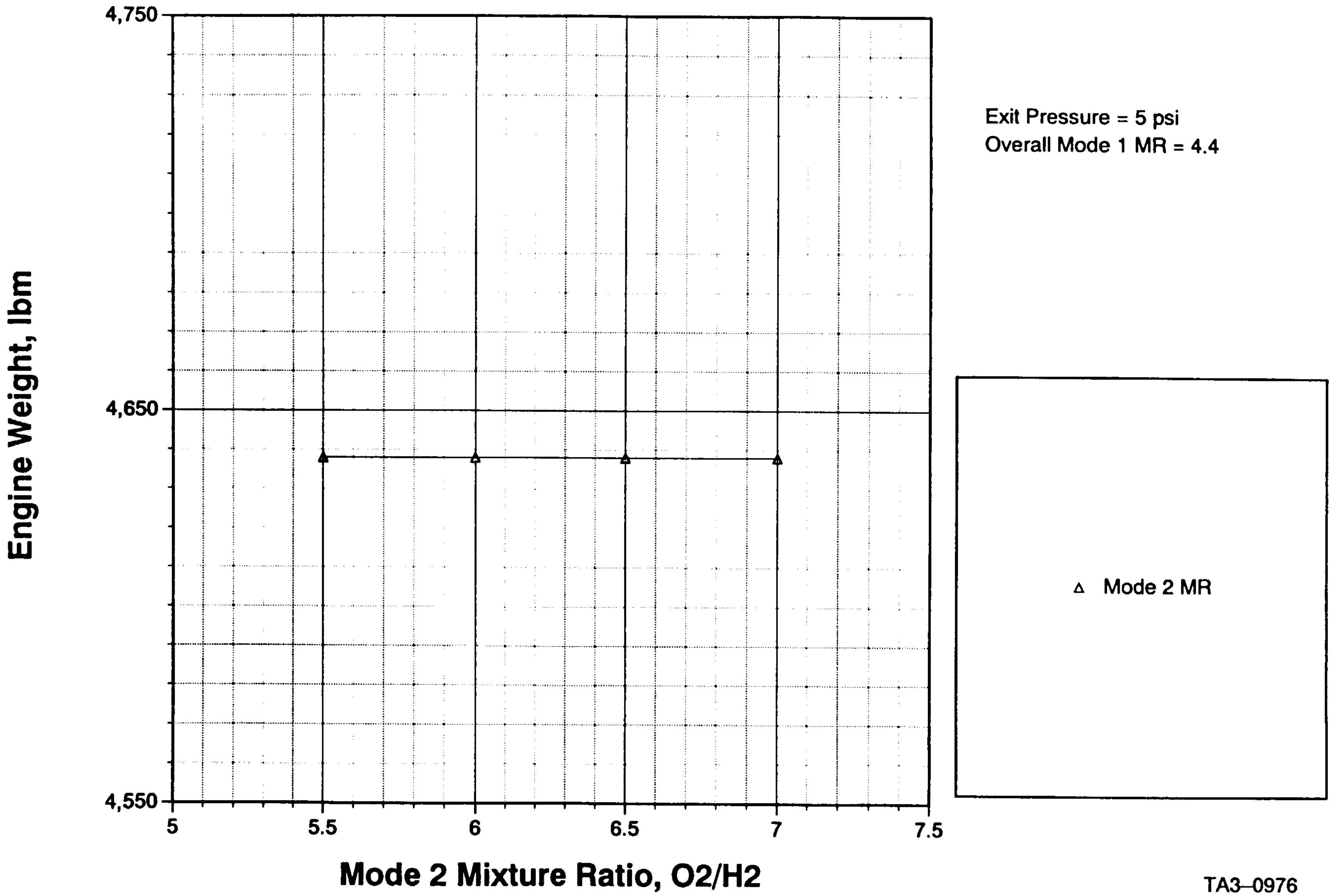


TA3–0963

Single Chamber Mode 2 Mixture Ratio

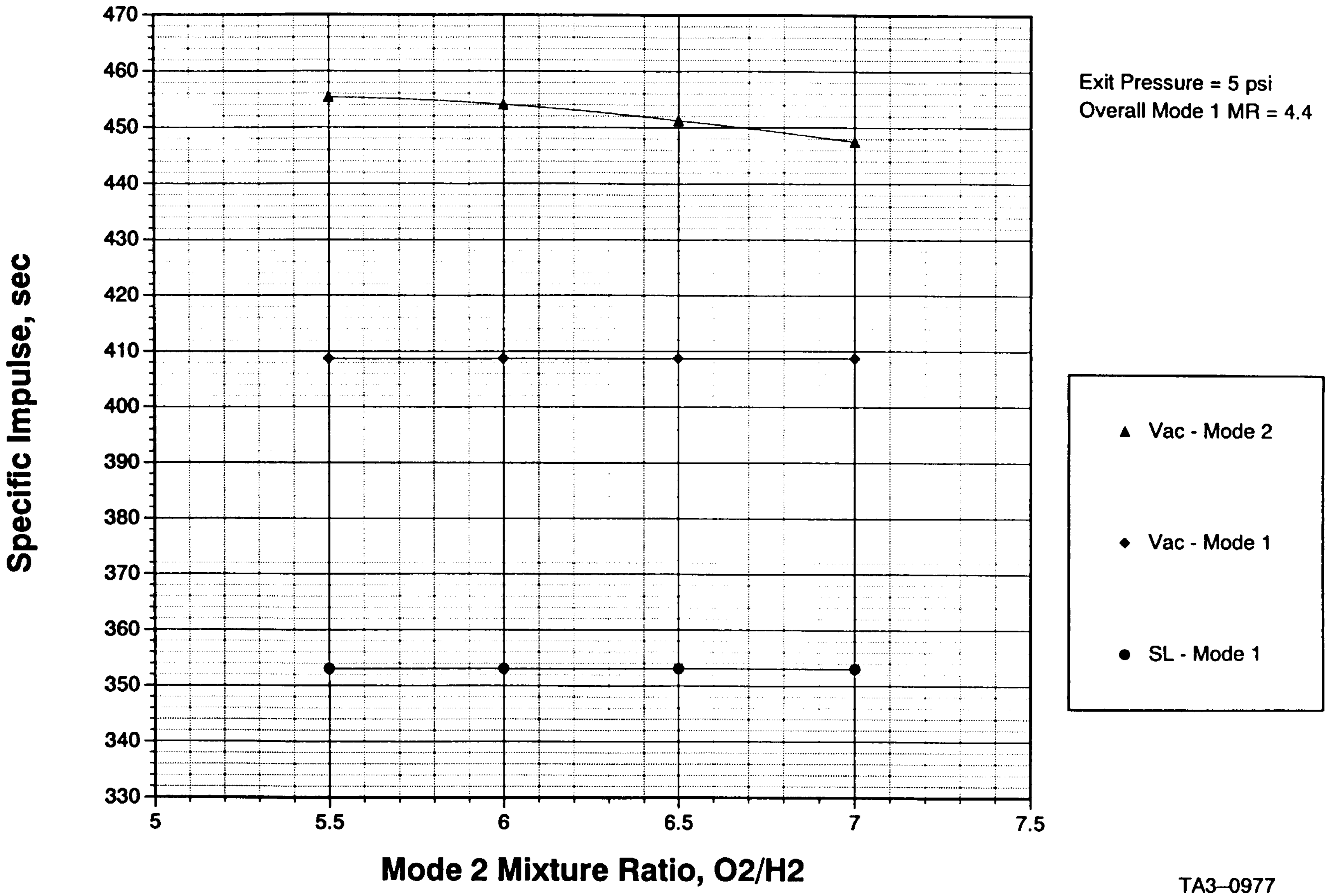
TA3–0863o

Engine Weights – FFSCC
Tripropellant Single Chamber



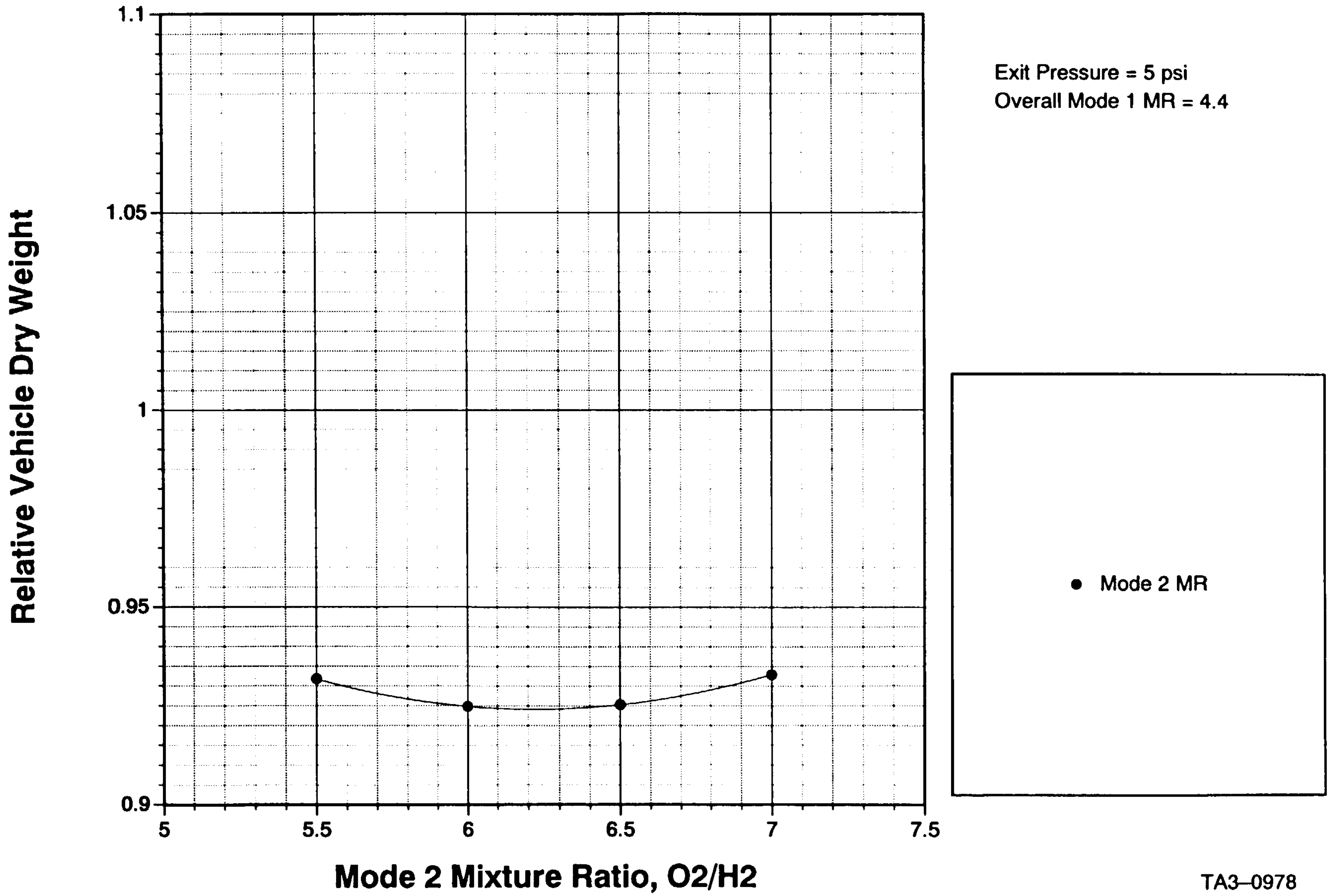
TA3–0976

Engine Performance – FFSCC
Tripropellant Single Chamber



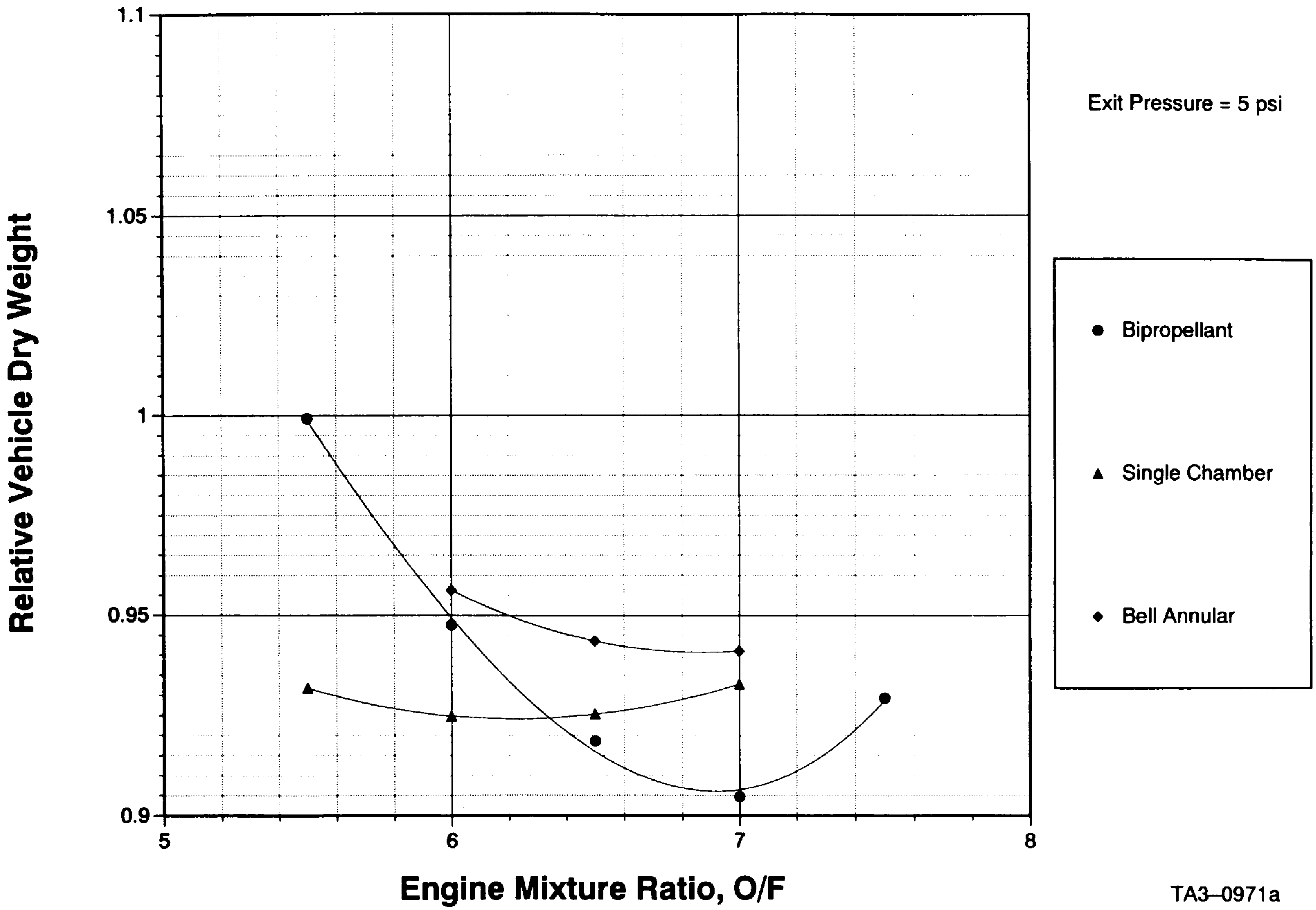
TA3–0977

SSTO Performance
Tripropellant Single Chamber – FFSCC



TA3–0978

SSTO Performance
Engine O_2/H_2 Mixture Ratio Variation



TA3–0971a

Alternate Propulsion Subsystem Concepts
Baseline Parameter Selections

	Single Chamber Tripropellant	Annular Tripropellant	Bipropellant
Nozzle Exit Pressure, psi	6.0	5.5	4.5
Mode 1 Mixture Ratio	4.4	—	—
Mode 2 Mixture Ratio	6.2	—	—
O_2/RP Mixture Ratio	—	2.8	—
O_2/H_2 Mixture Ratio	—	6.8	6.9
Percent Hydrogen, %	6	—	—
Mode 1 O_2/RP to O_2/H_2 Thrust Split	—	H_2 Cooling Limit	—

TA3–0878b

Resulting Nominal Engines

	Single Chamber Tripropellant	Bell Annular Tripropellant	Bipropellant Closed Cycles	Bipropellant Gas Generator
Thrust, Sea Level, lbf	421,000	421,000	421,000	421,000
Thrust, Vacuum, lbf	477,630	478,701	484,585	486,706
Specific Impulse, sec				
Mode 2 Vacuum	450.69	461.13	451.43	445.28
Mode 2 Sea Level	339.18	267.33	392.19	385.16
Mode 1 Vacuum	406.26	369.33	451.43	445.28
Mode 1 Sea Level	358.09	324.81	392.19	385.16
Chamber Pressure, psi				
Mode 1	4,000	4,000	4,000	4,000
Mode 2	1,966	4,000	4,000	4,000
Area Ratio				
Mode 1	63.56	59.60/64.54*	69.77	69.84
Mode 2	63.56	226.73	69.77	69.84
Engine Weight, lbm (Uncoated/Coated)				
FFSCC	4,492 / 4,176	4,473 / 4,201	4,567 / 4,242	—
ORSCC	4,610 / 4,295	—	—	—
FRSCC	4,040 / —	4,189 / —	4,049 / —	—
Hybrid Cycle	4,161 / 4,026	4,528 / 4,227	4,058 / —	—
Gas Generator Cycle	—	—	—	— / 3,629

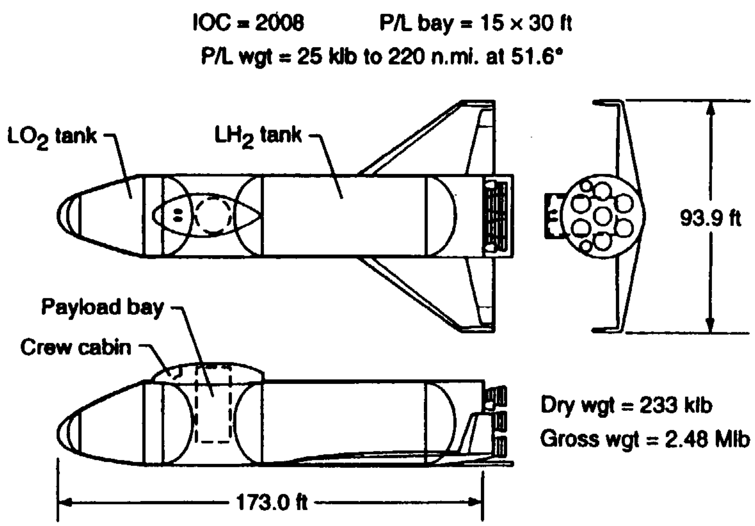
* $(O_2/H_2)/(O_2/RP)$

TA3–1129a

Tripropellant Comparison Study
Engine Weights and Vehicle Performance

TA3–0863f

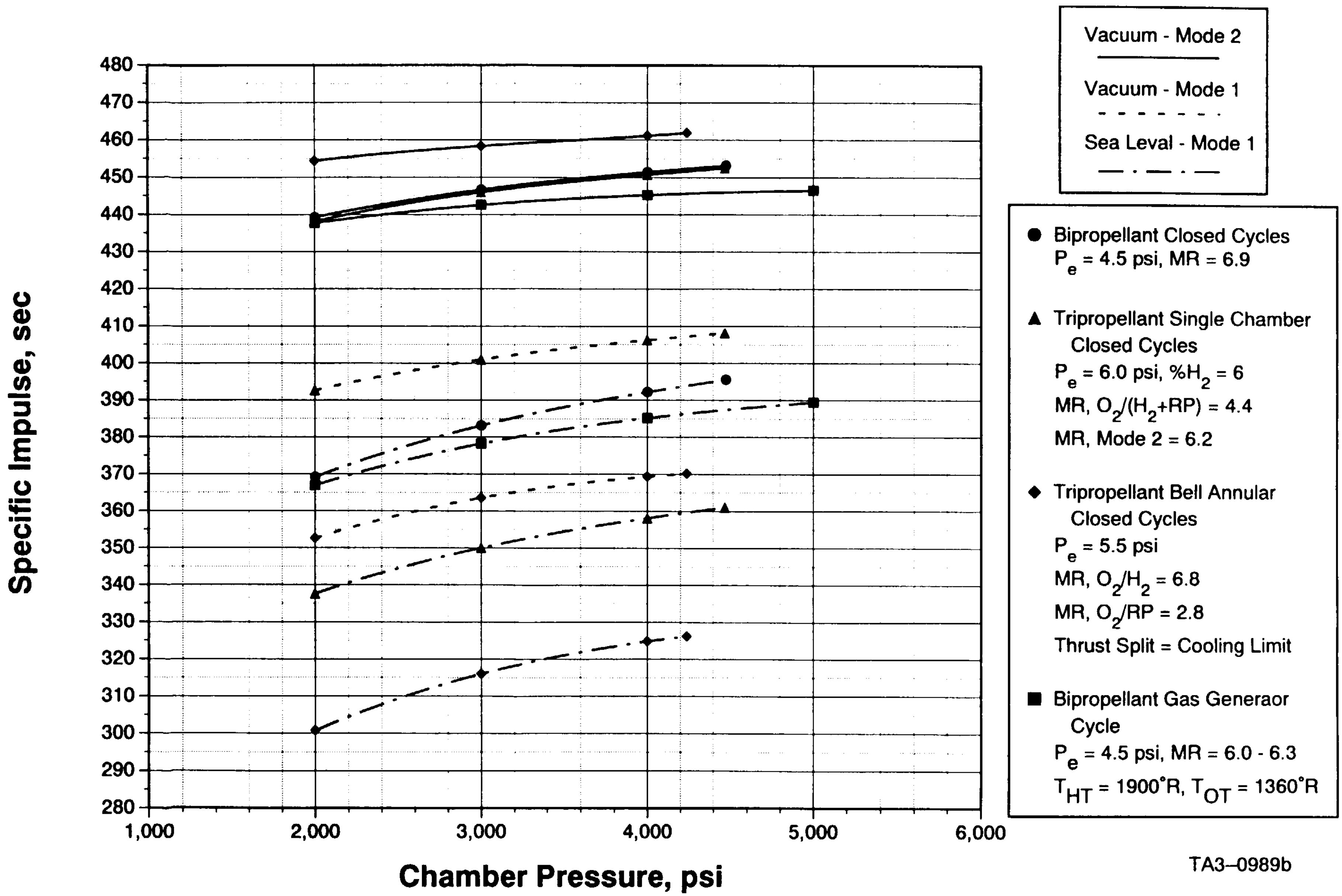
Tripropellant Comparison Study
Mission Groundrules



- Consistent With Option 1 Evaluation
- RLV Application
  - SSTO
  - 25K Payload
  - 220 NMi, 51.6°
- Option 3 Winged Vehicle
- CONSIZE and POST
  - Choose a Version of CONSIZE with LaRC
    - Bipropellant
    - Tripropellant
  - Freeze the Choice for Remainder of Task
  - April/May 1994 Version Used
    - Consistent Tripropellant and Bipropellant Models

TA3-0719e

Engine Performance Specific Impulse Performance



TA3–0989b

Tripropellant Comparison Study
Helium Usage

- Engine Requirements

  - SSME
    - Start and Shutdown Purges
      - Majority of Usage
    - Turbomachinery Interpropellant Seal Purges During Operations
      - Only for Turbopumps with Dissimilar Working Fluids
        - e.g., Fuel Rich Preburner Powering Oxygen Pump
      - Solid Seal

  - Future Engines
    - Turbomachinery Interpropellant Seal Purges During Operations
      - Segmented Seals
        - Much Lower He Requirements

TA3–1145

Tripropellant Comparison Study
Helium Usage

- All Future Engines are Expected to Need Very Little He Compared to SSME

- Use

  Flowrate (lbm/sec) = 0.0000264*D*P

  D = shaft diameter (inches)
  P = purge pressure (psi)
  100 psi is reasonable pressure

  - Once for Each Turbopump with Dissimilar Working Fluids

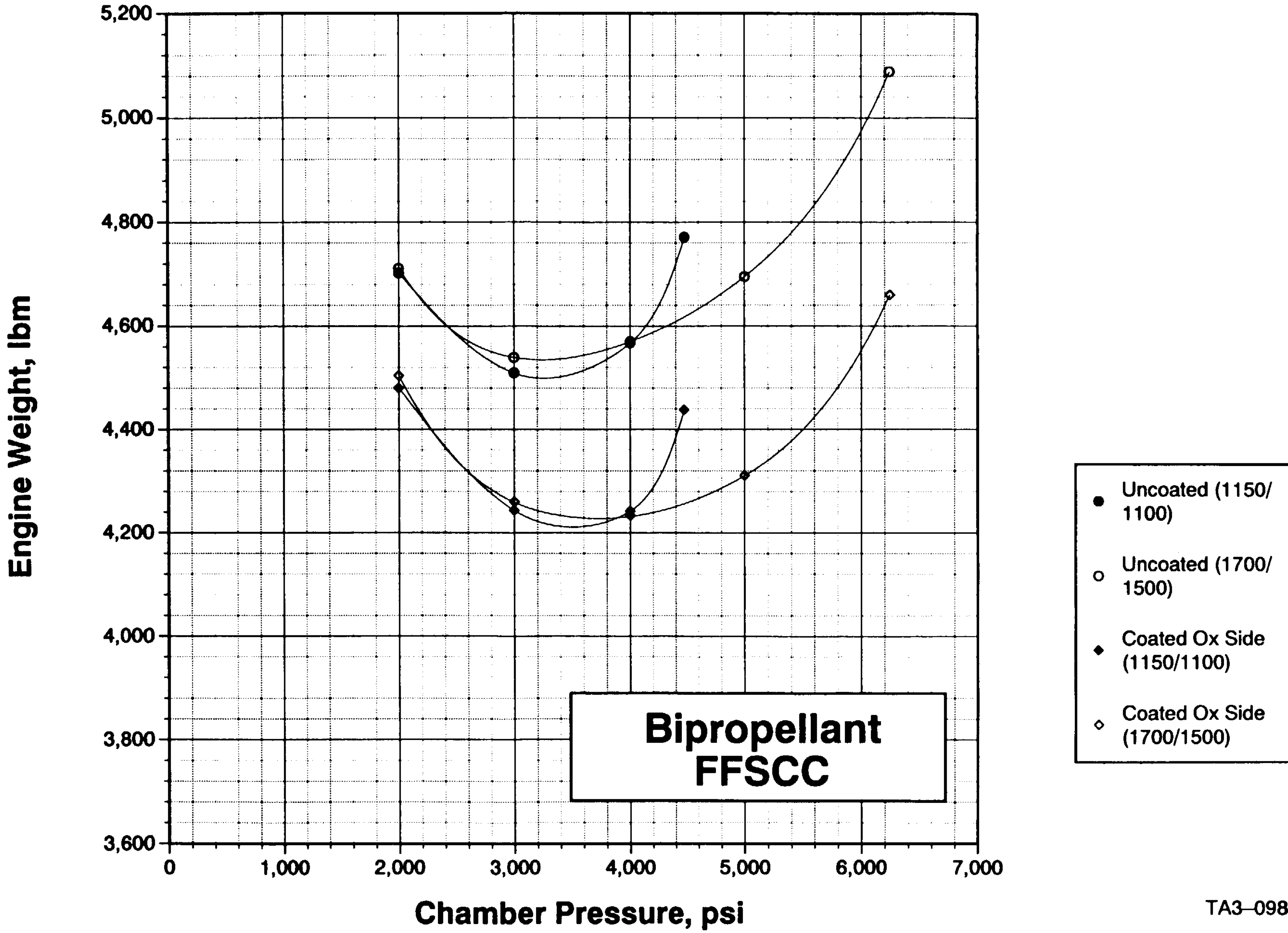
- CONSIZ He Constant of ~ 4.5E-5, of Which 3.83E-5 is Vehicle Usage, is Typical of Cycles Needing Interpropellant Seals

- Effect on Vehicle Dry Weight is Small with Future Engines
  - ~ 500 lbm

- Not a Cycle Discriminator with Future Engines

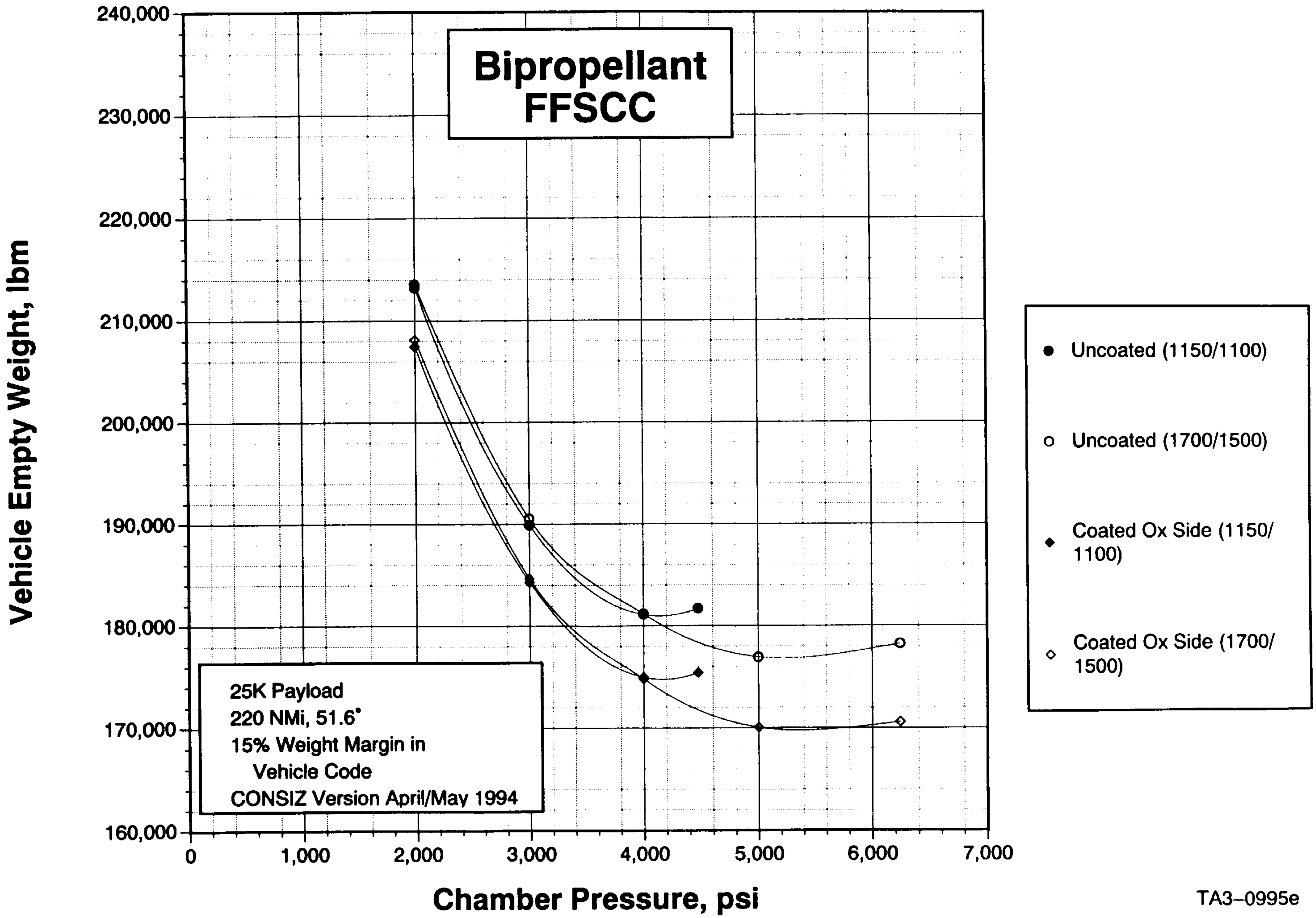
TA3–1145

Effect of Turbine Temperature
on Engine Weights



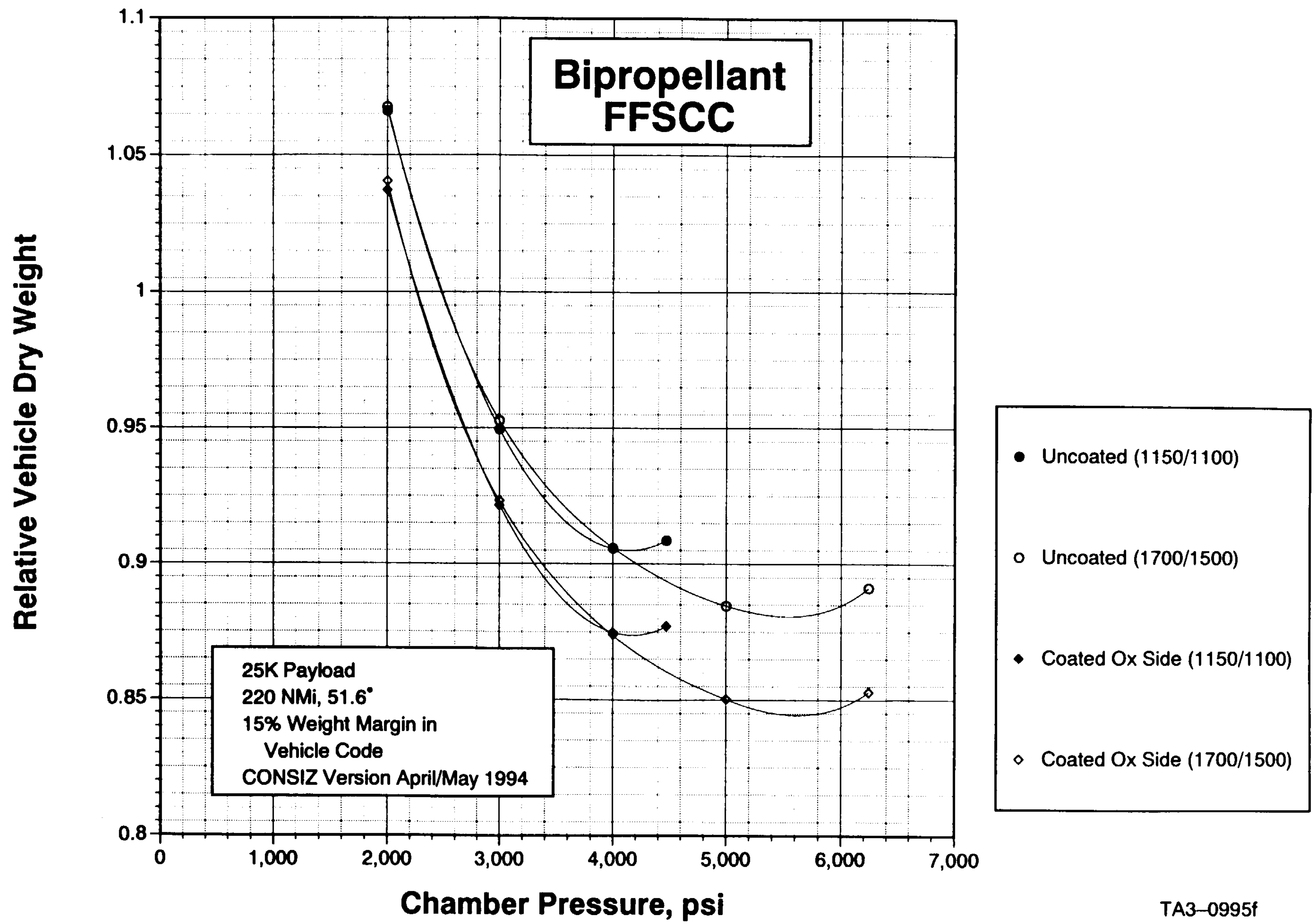
TA3–0983f

Effect of Turbine Temperature on SSTO Performance



TA3–0995e

Effect of Turbine Temperature on SSTO Performance



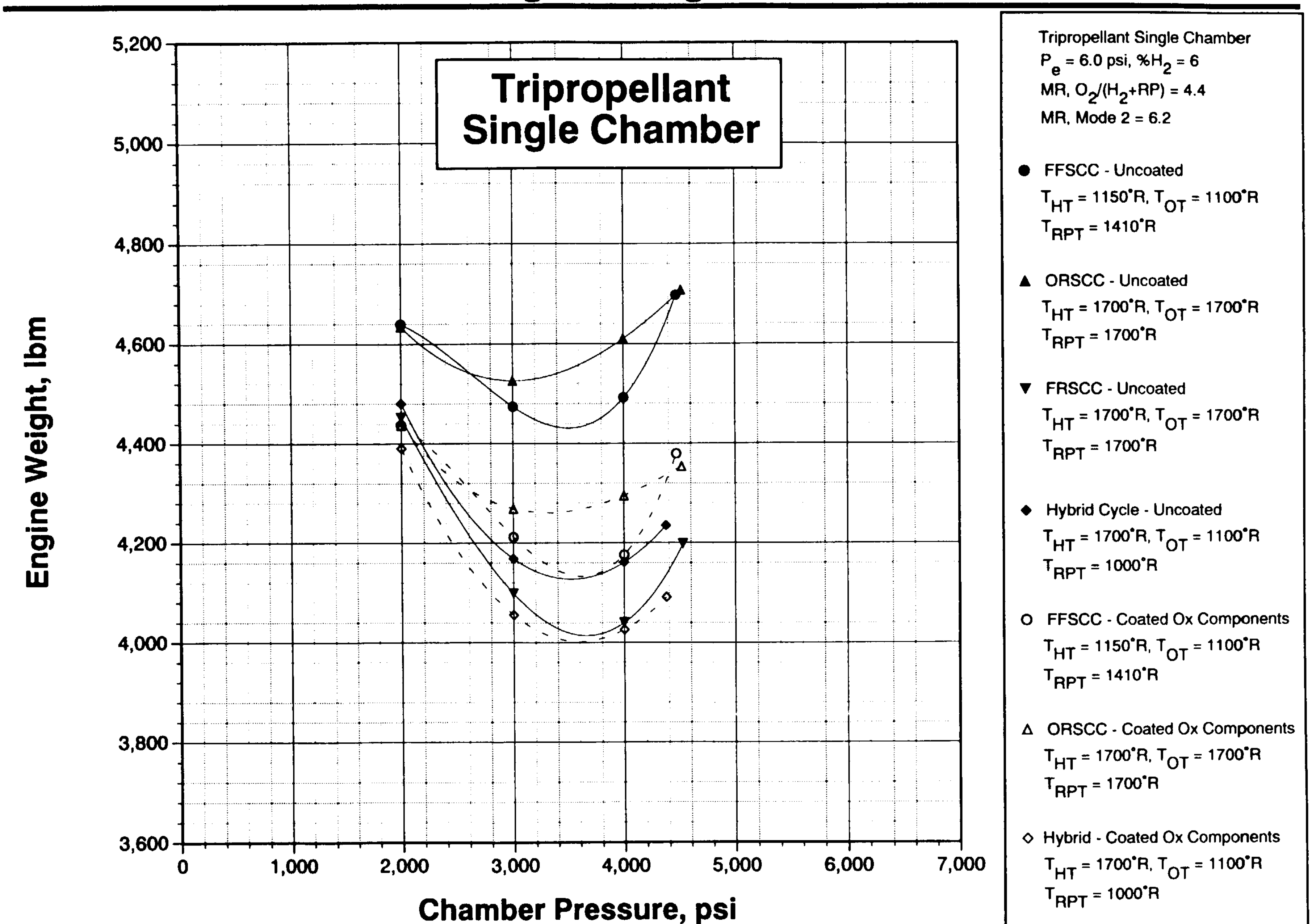
TA3–0995f

Tripropellant Comparison Study
Effects of Turbine Temperature

- Turbine Temperatures Can Extend Chamber Pressure Capabilities
  - Effect on Vehicle Dry Weight Decreasing Significantly Above ~ 4,000 psi
  - 4,000 psi About Limit of Consideration for Next Generation Engines
- Turbine Temperatures Have No Appreciable Effect on Engine Weight
  - Except Just Before the Power Limit for That Temperature
- Lower Turbine Temperatures Will Reduce the Thermal Environment and Improve Engine Margins, Life and Operations
- Net Effect
  - All Design Points Will Use Those Turbine Temperatures That Will Produce a Power Limit of Around 4,500 psi Chamber Pressure
    - Lowest That Will Not Effect Engine Weight Below ~ 4,000 psi Chamber Pressure

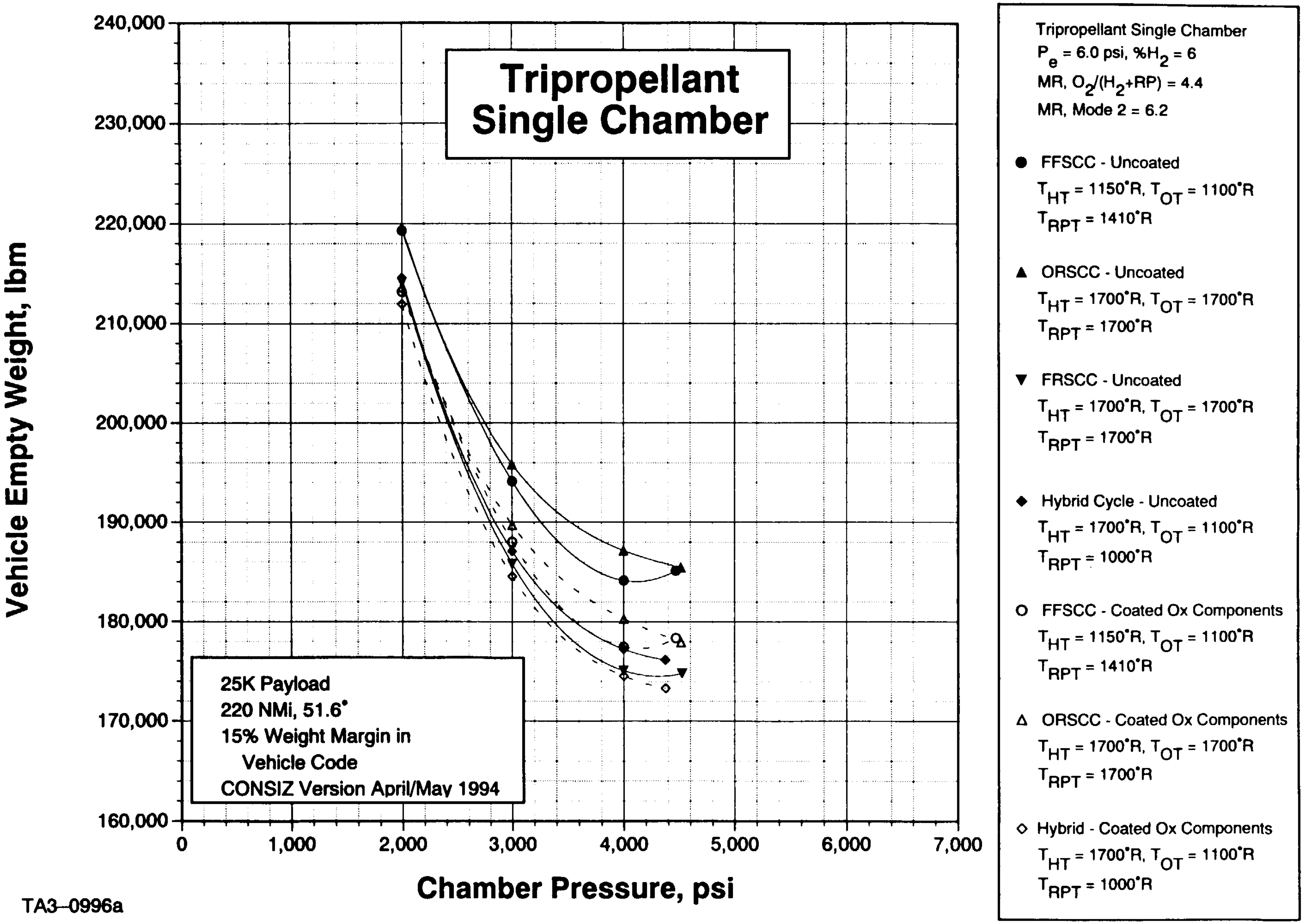
TA3–1137

Engine Weights



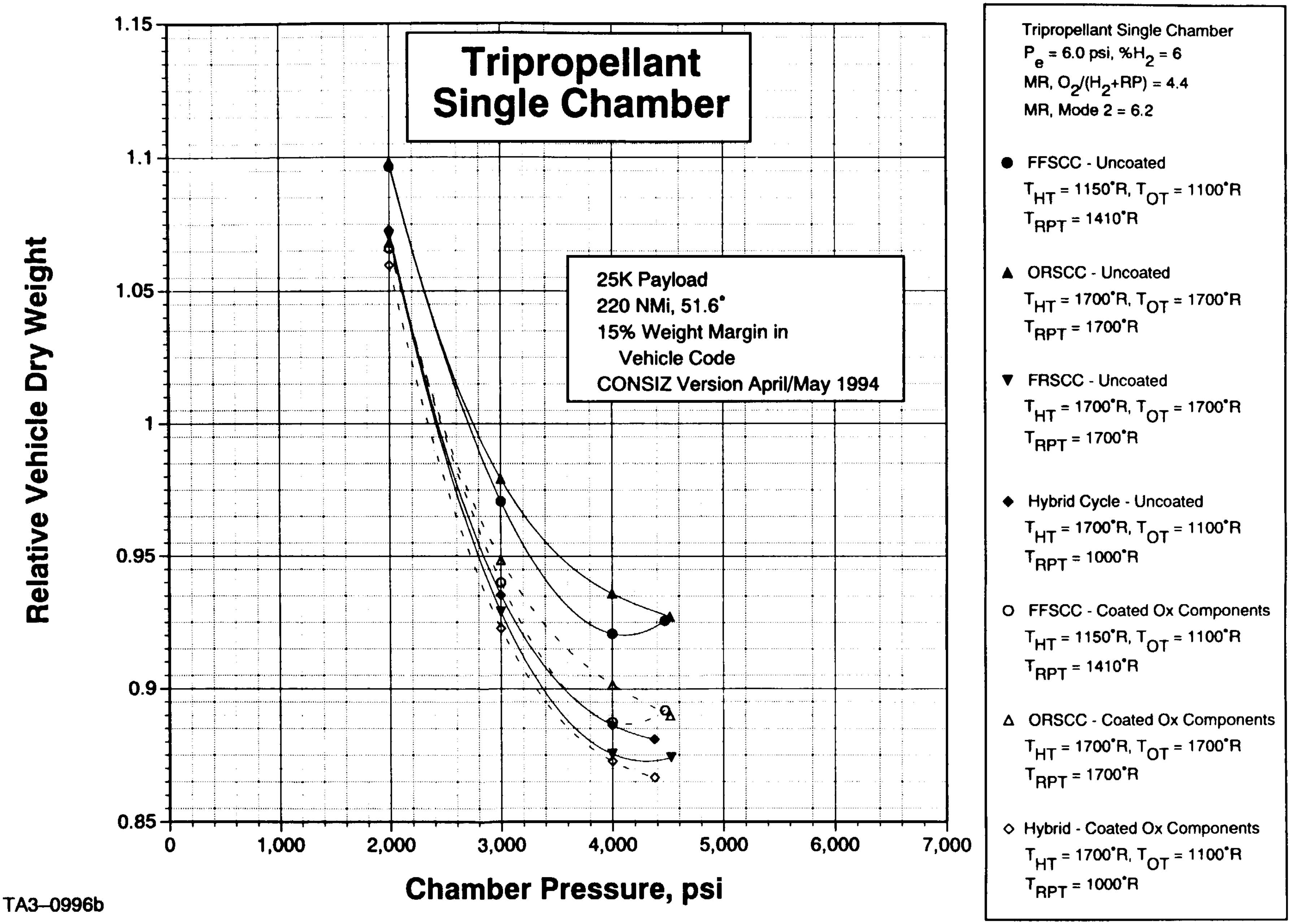
TA3–0996

SSTO Performance



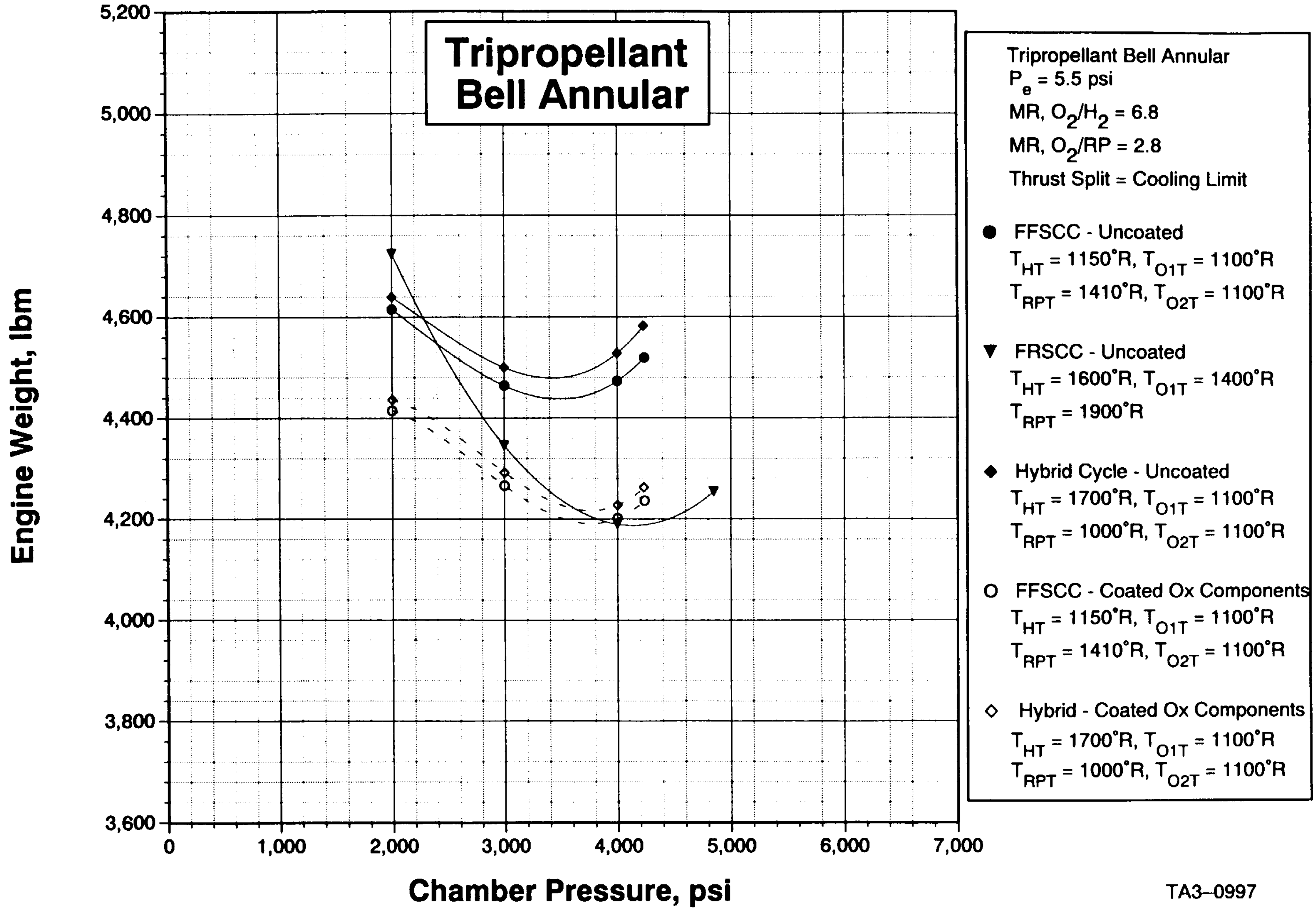
TA3–0996a

SSTO Performance



TA3–0996b

Engine Weights



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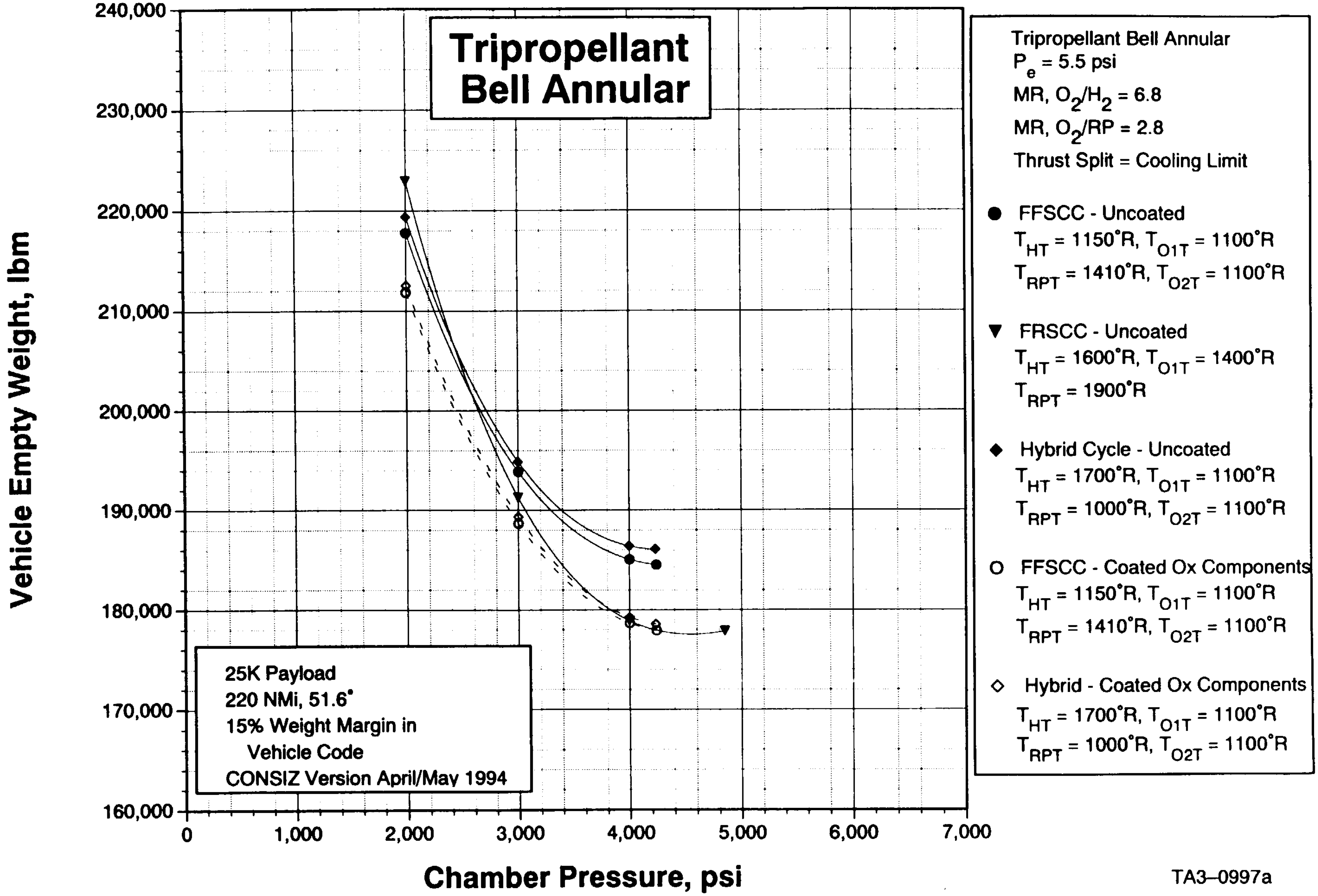
SSTO Performance



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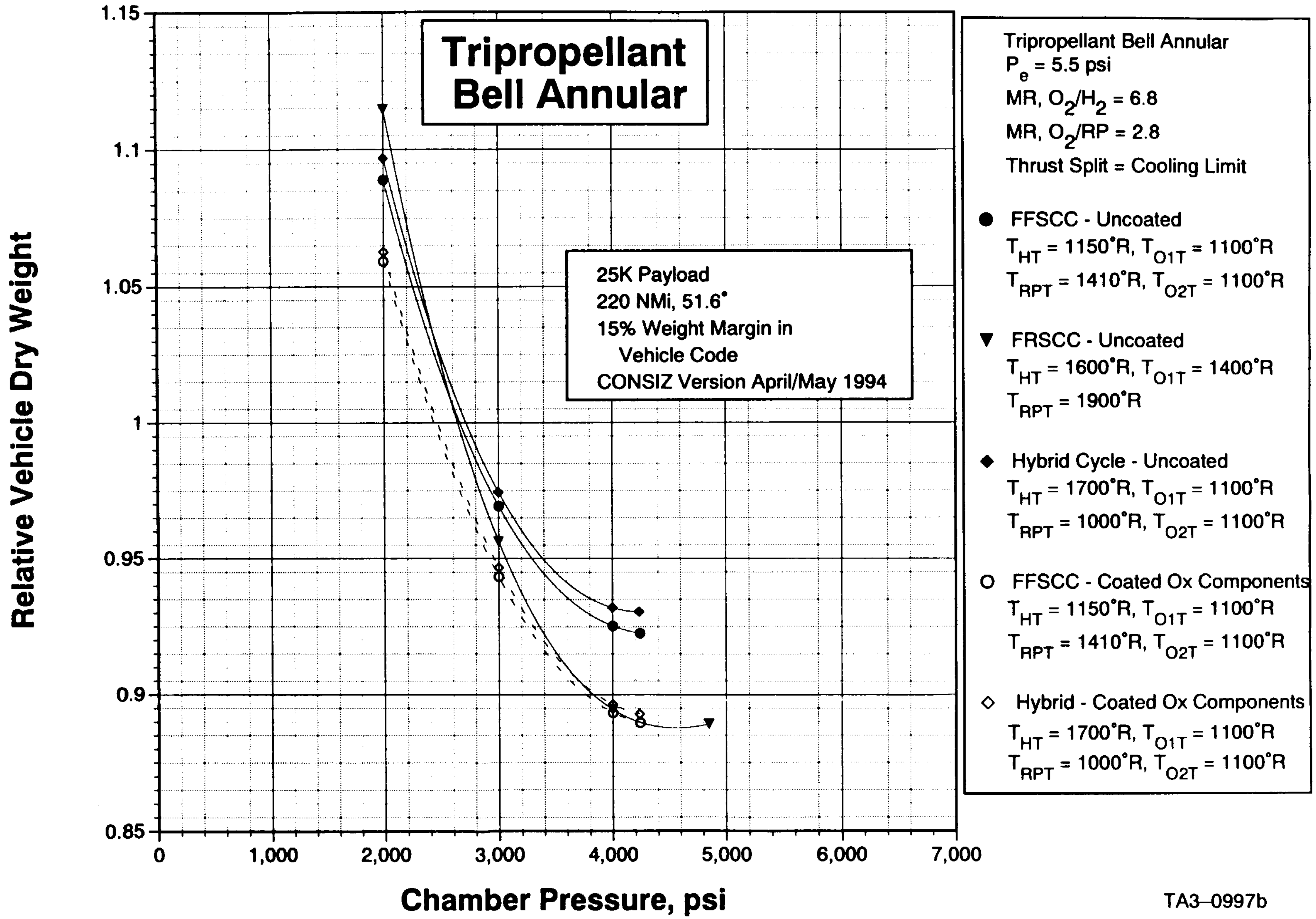
SSTO Performance



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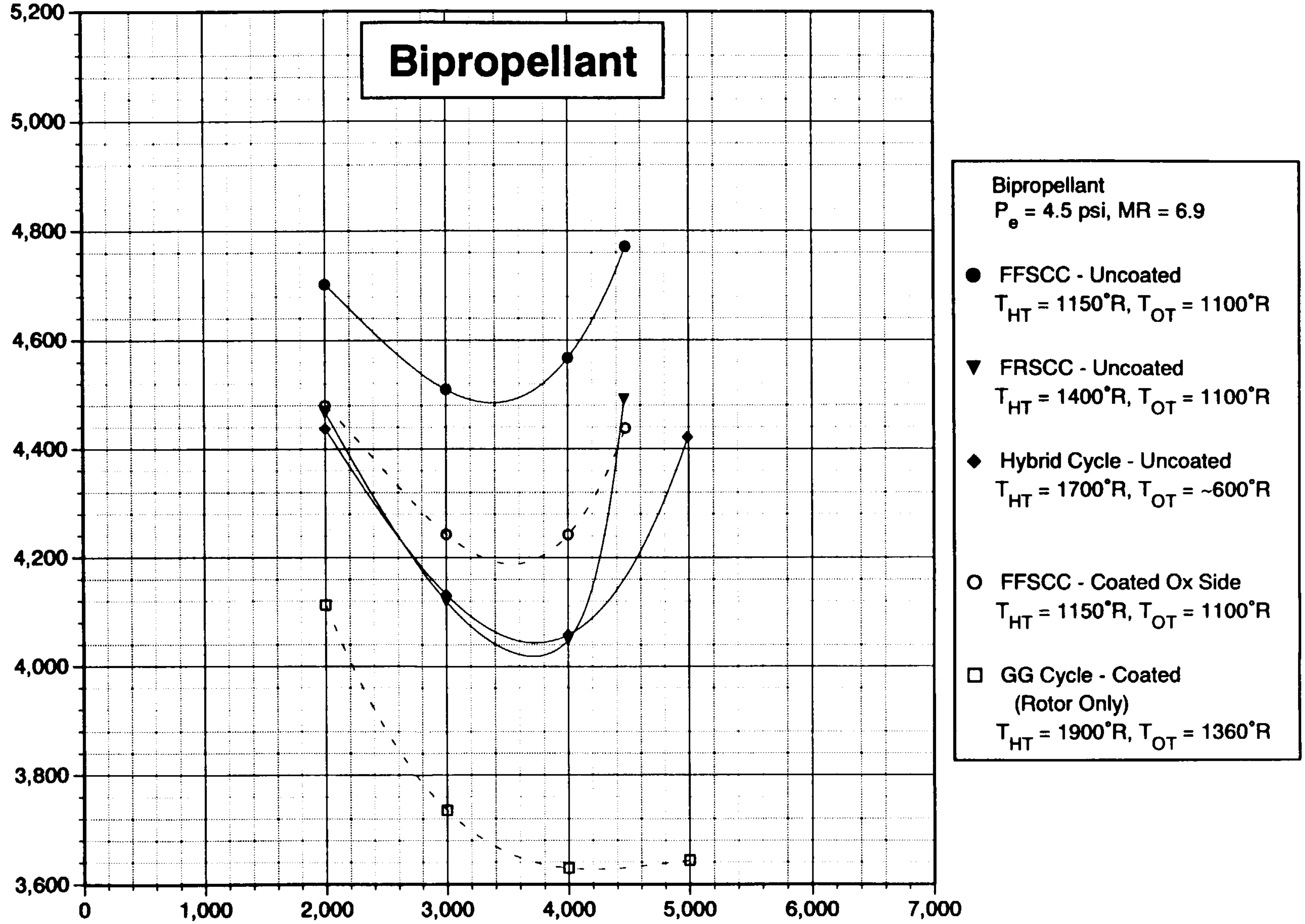
Engine Weights



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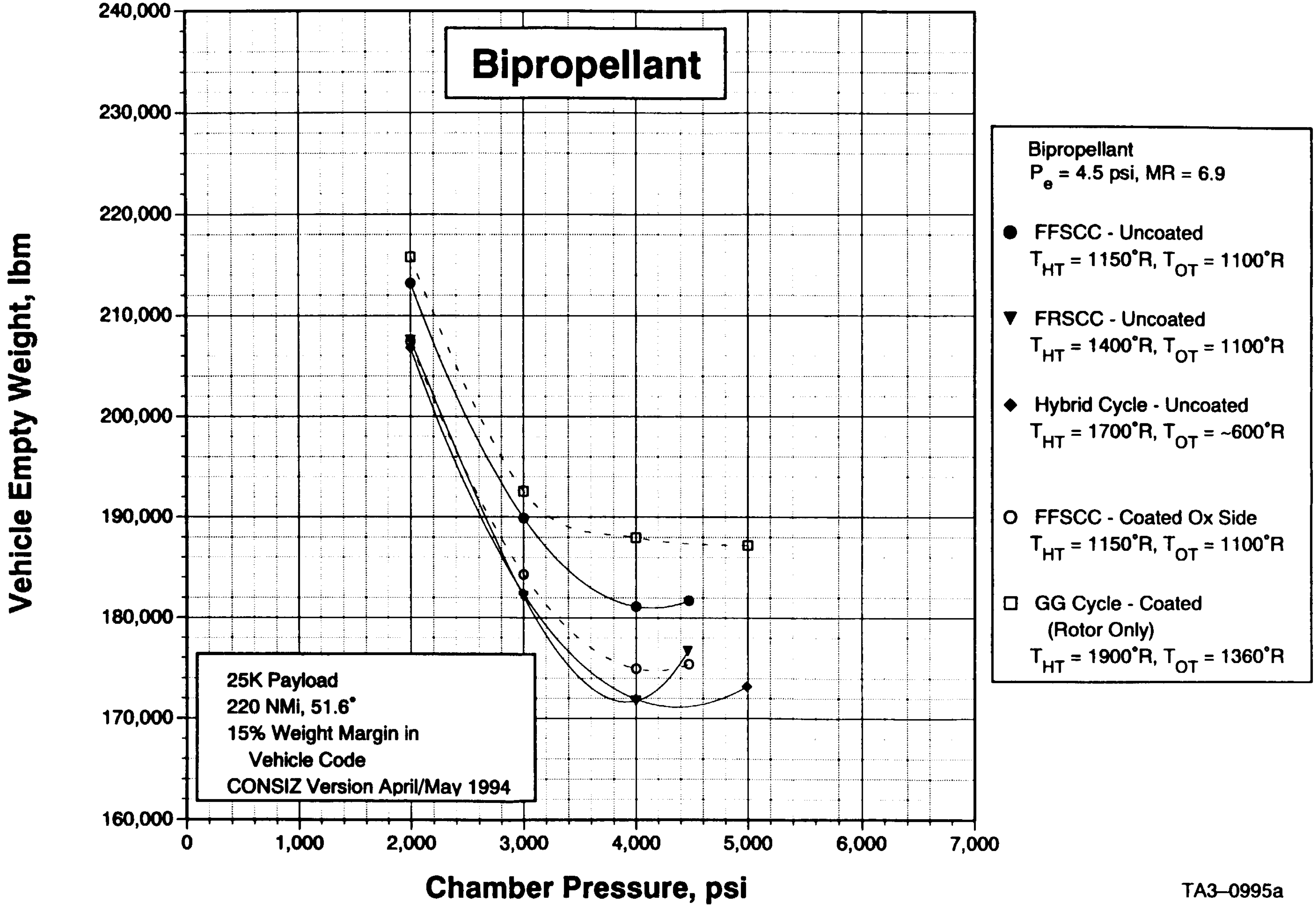

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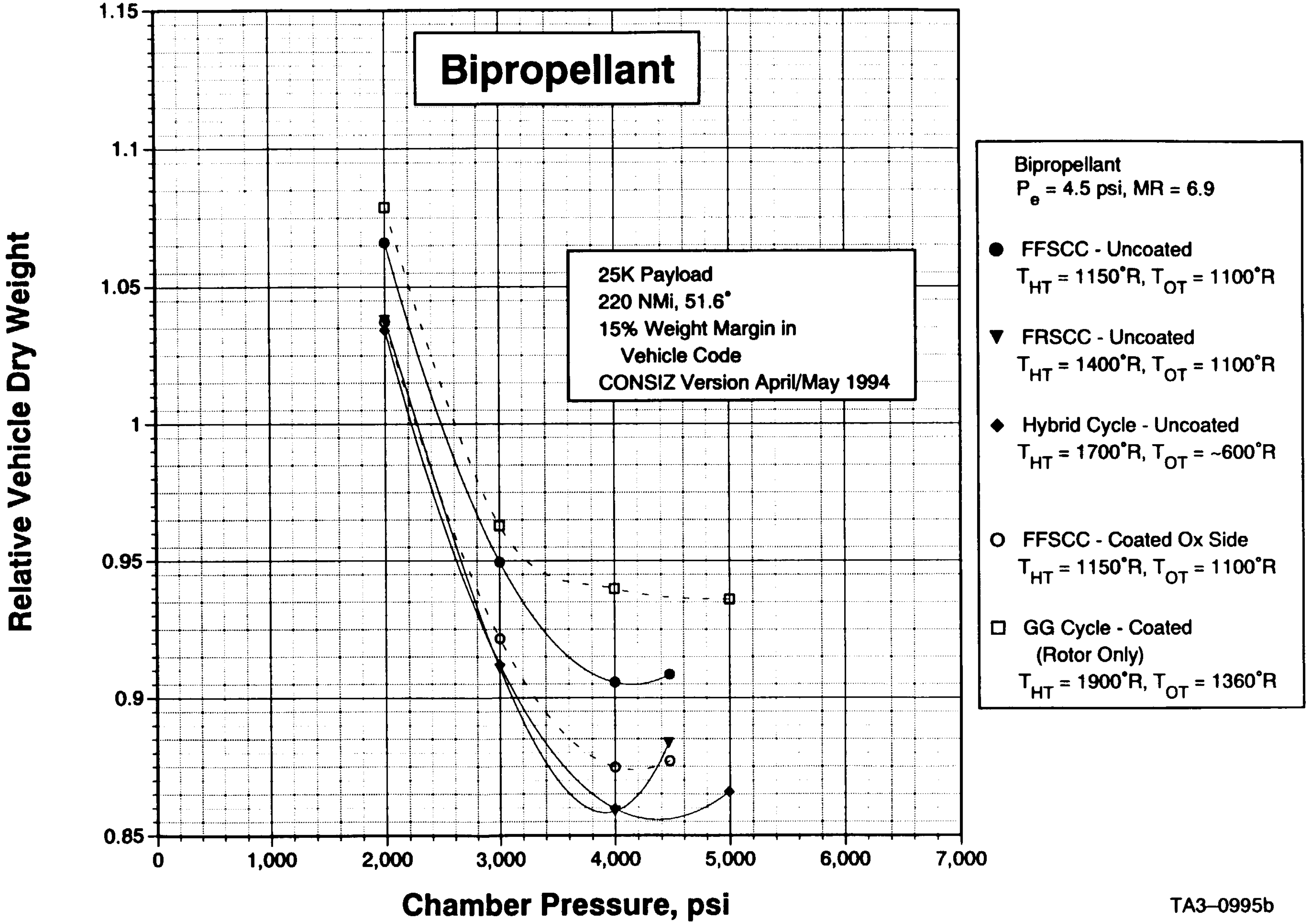


TA3–0995b

Tripropellant Comparison Study

Cycle Observations

- GG Cycle Not Competitive for This Application

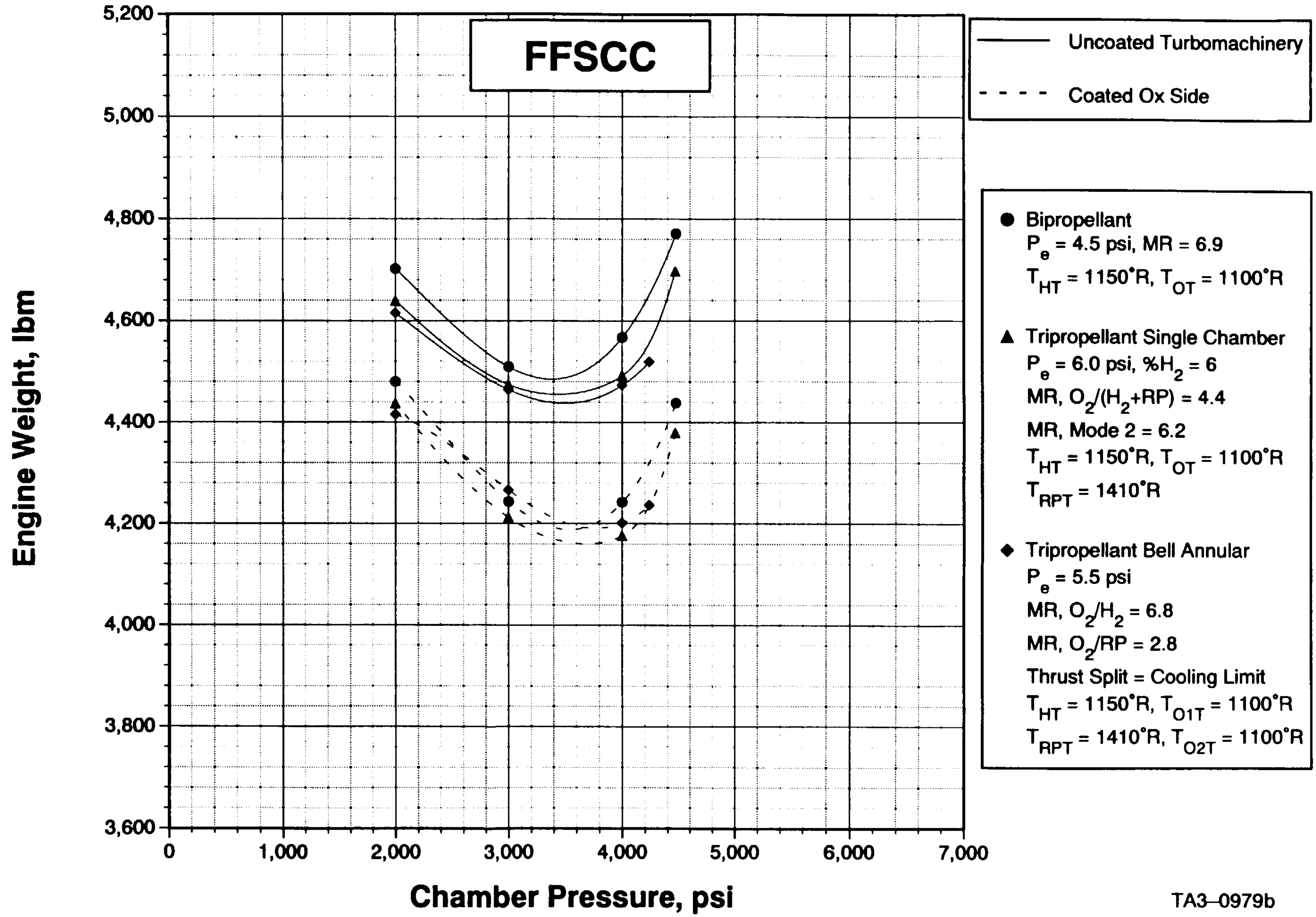
- FRSCC Always the Lightest Engine Weight
  - Temperatures at Cooled/Uncooled Powerhead Interface
  - Limited Temperature Margins

- All Cycles With Hot Ox Rich Gases
  - Greatly Benefit From Improved Strength Oxygen Resistant Materials
    - Technology Programs to Achieve Such Strength Materials is Feasible
  - Their Weights and Vehicle Dry Weight Performance Results Would Then Equal Their Coated Counterparts

- Use of Higher Strength Oxygen Resistant Materials or Use of Coatings Makes All Closed Cycles Approximately the Same
  - Allows Cycle Choice on Basis of Margins, Life, Operations

TA3–1138

Engine Weights



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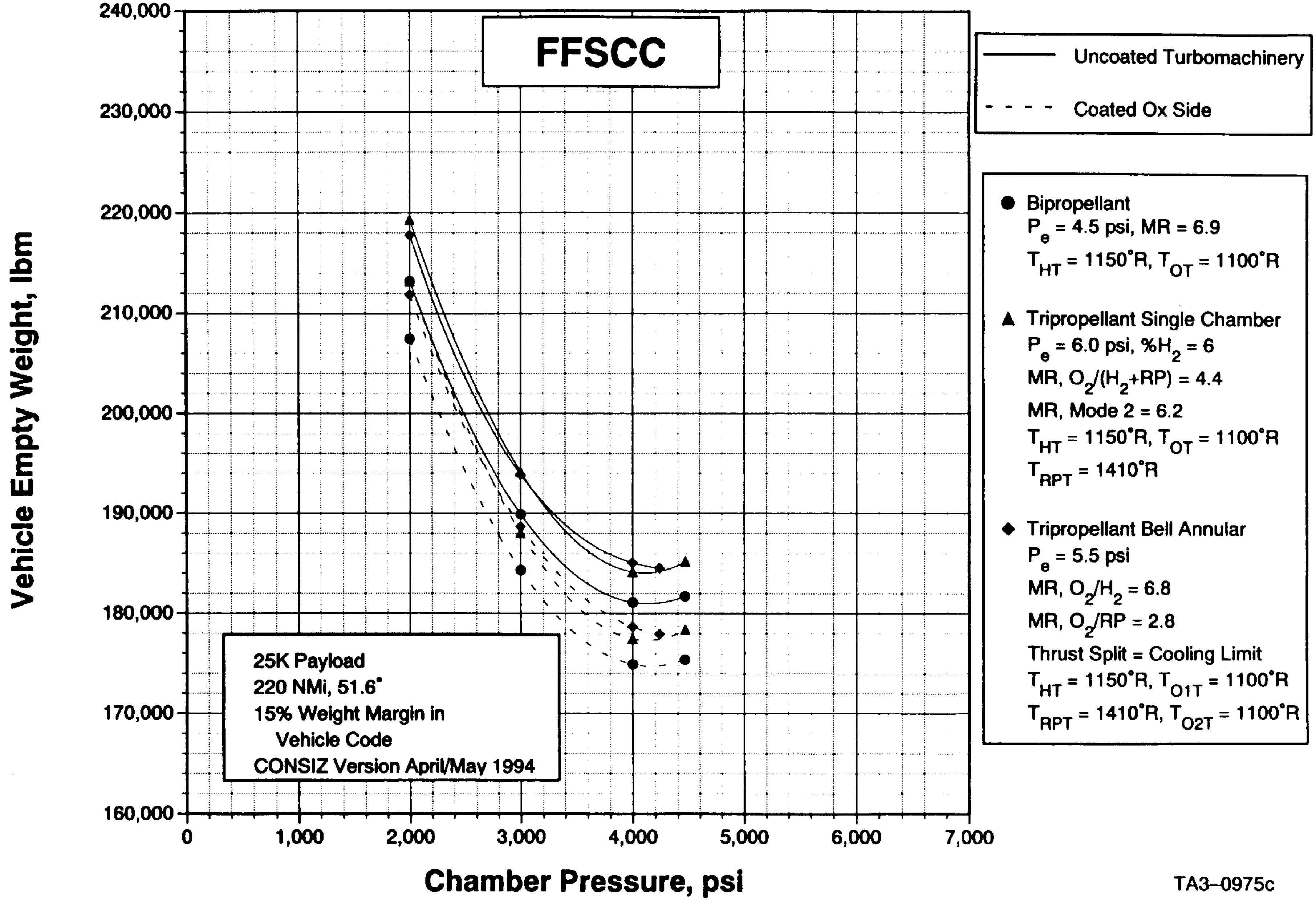
SSTO Performance



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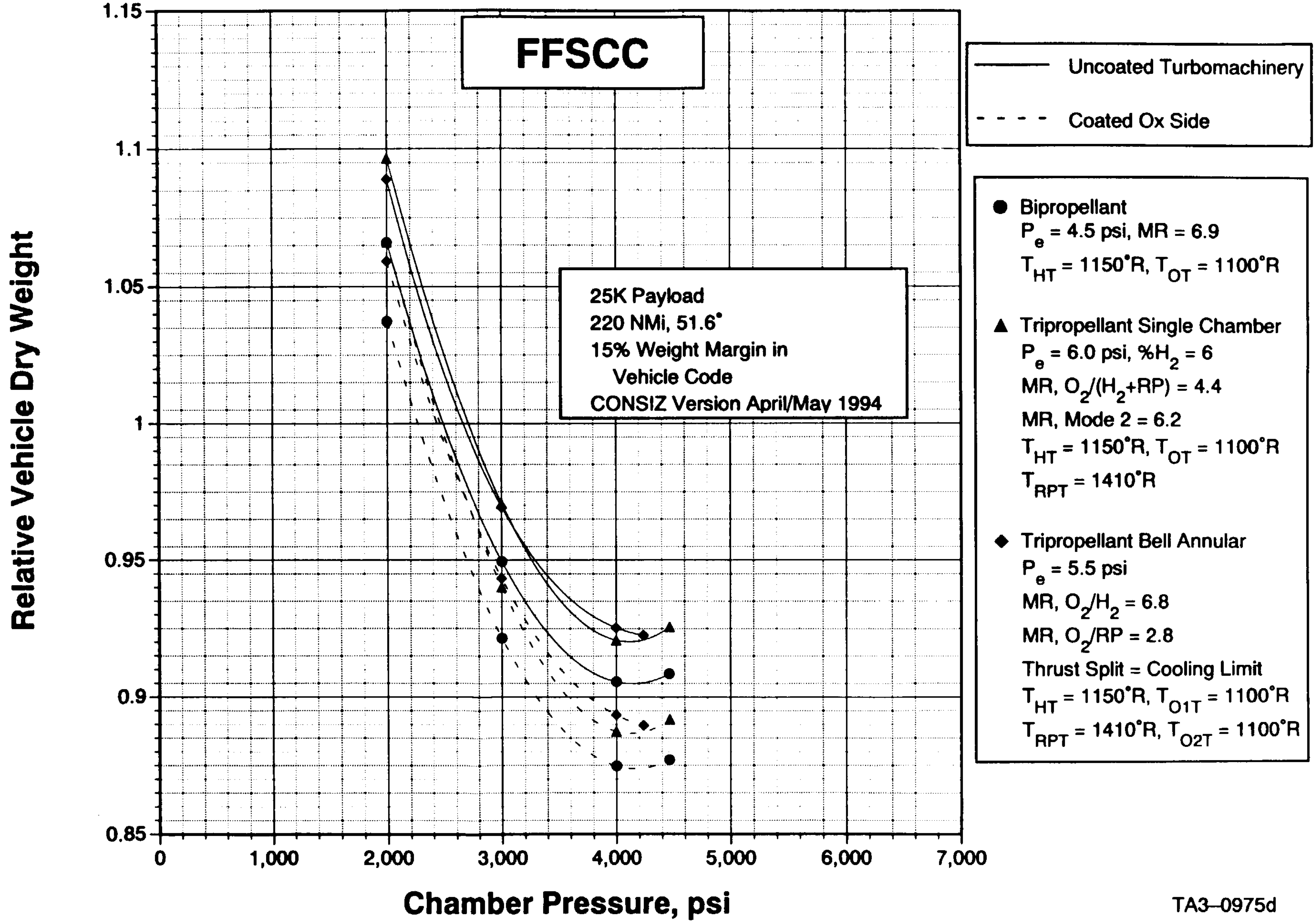

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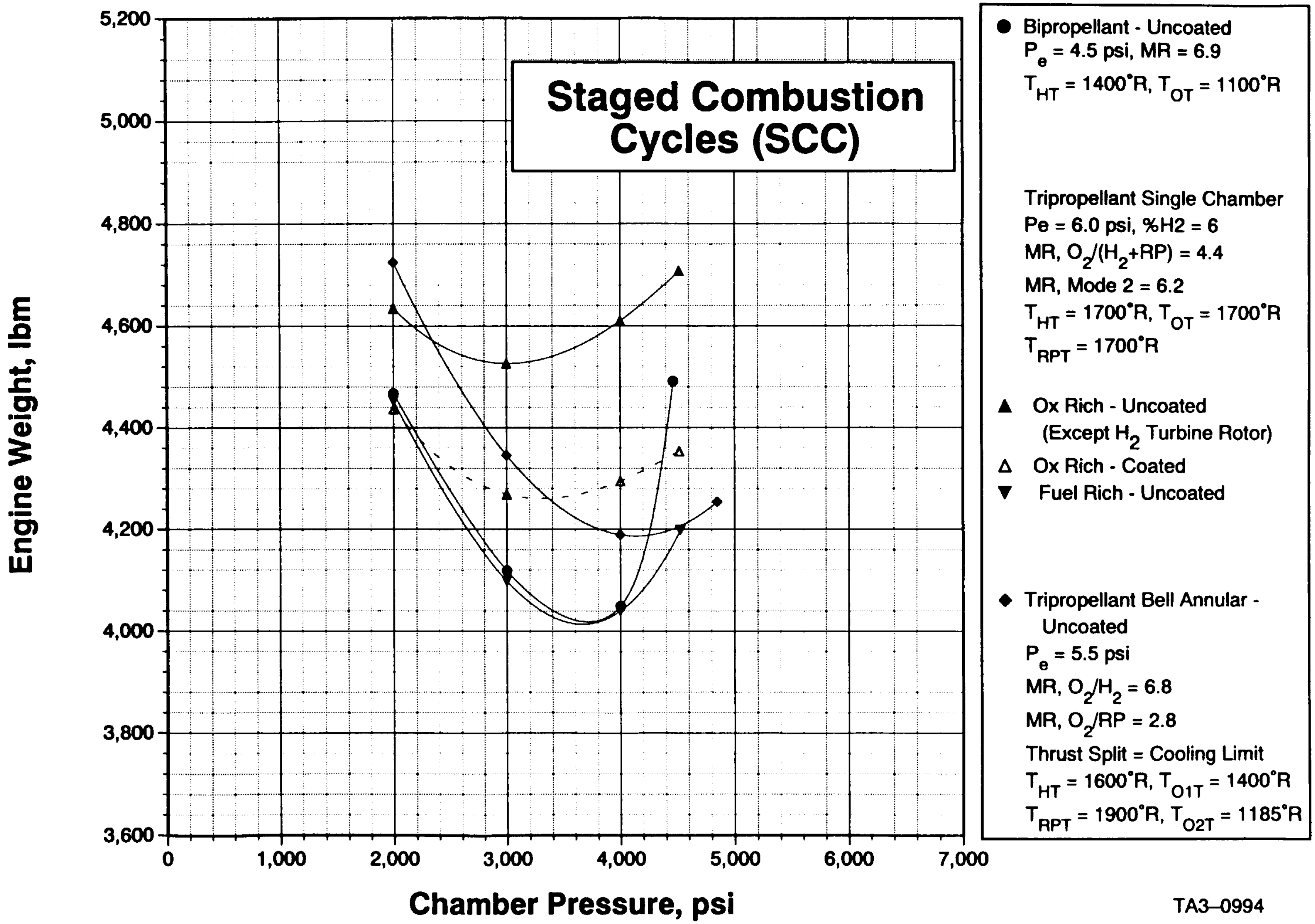
Engine Weights



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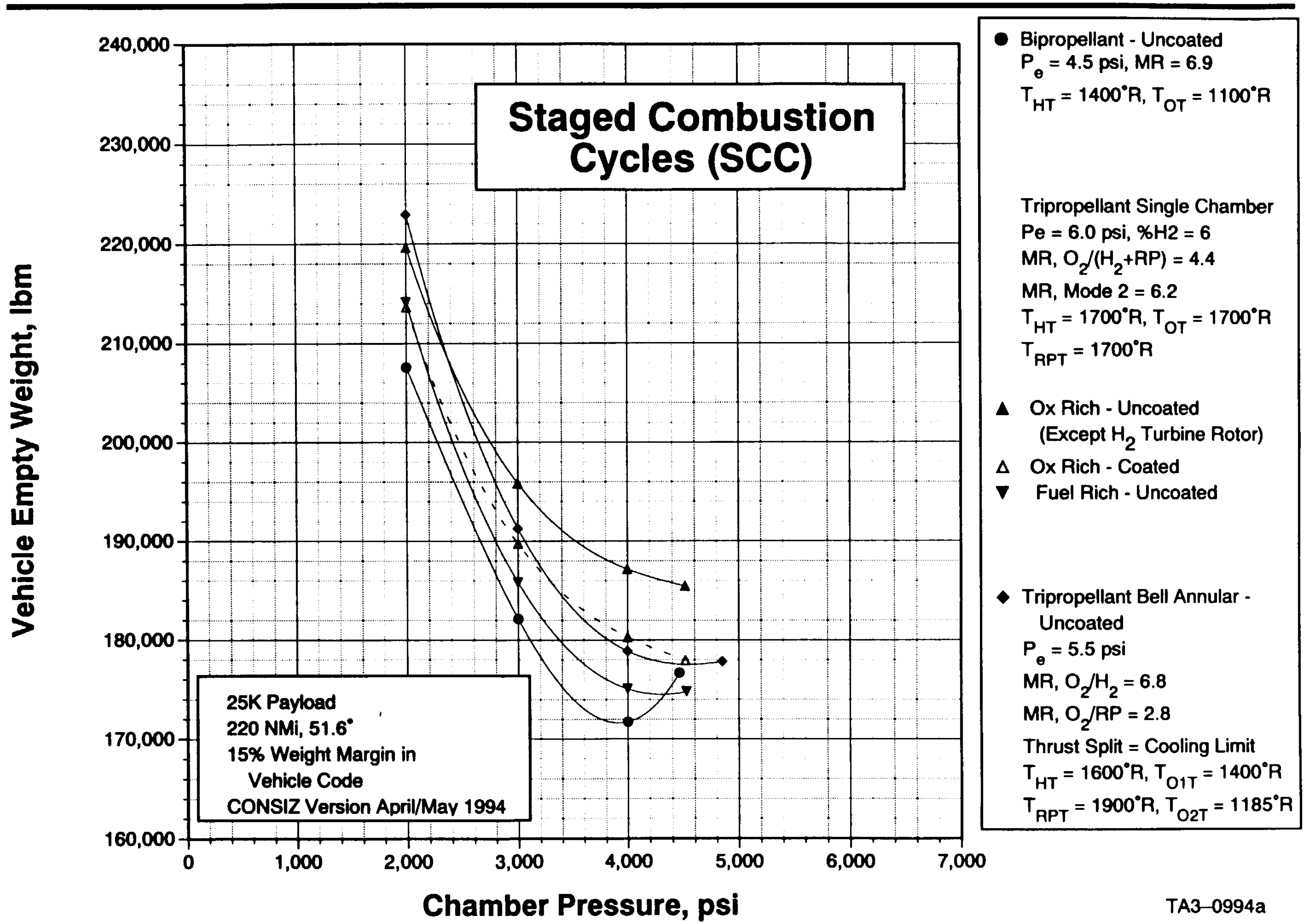
SSTO Performance



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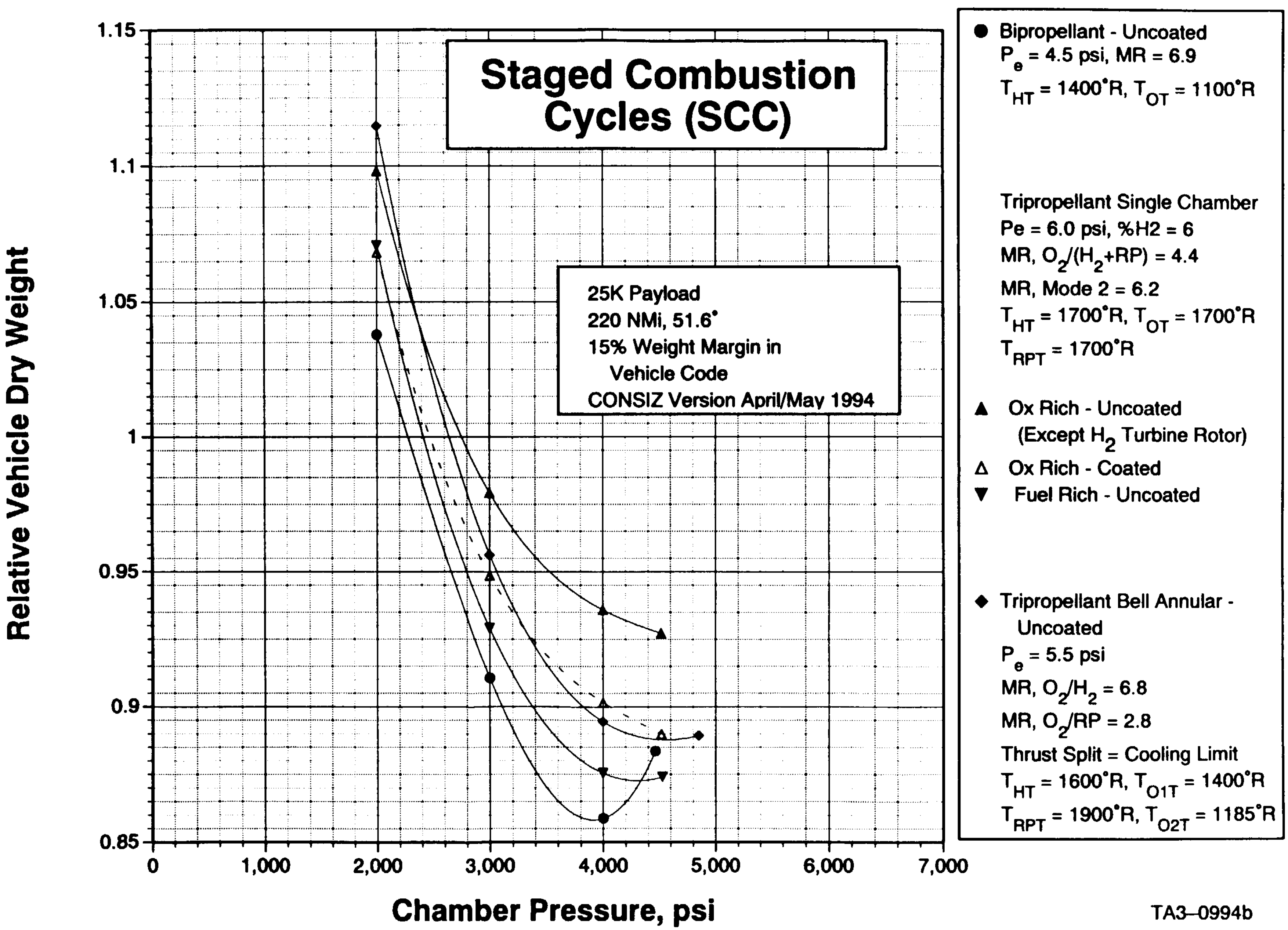

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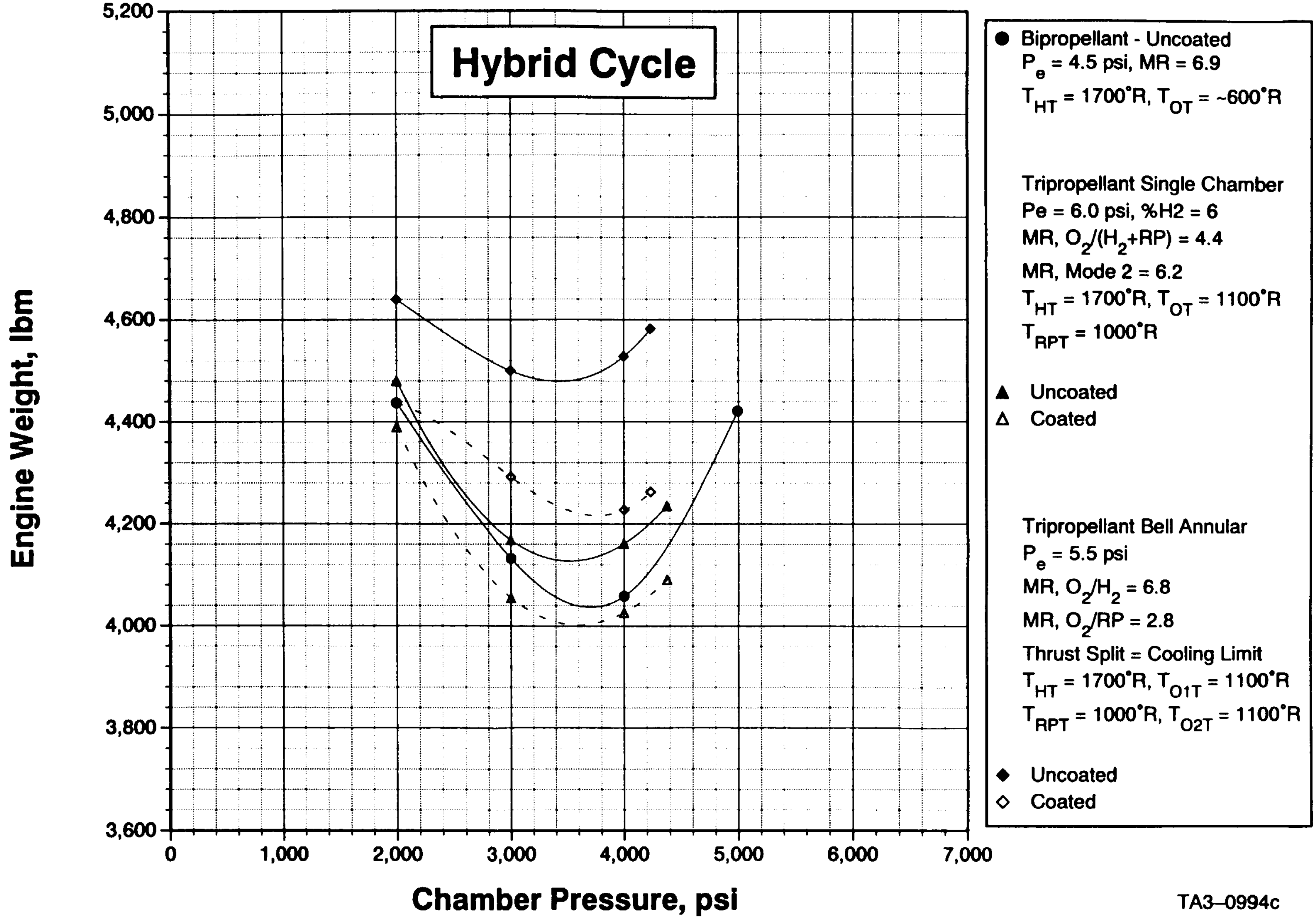
Engine Weights



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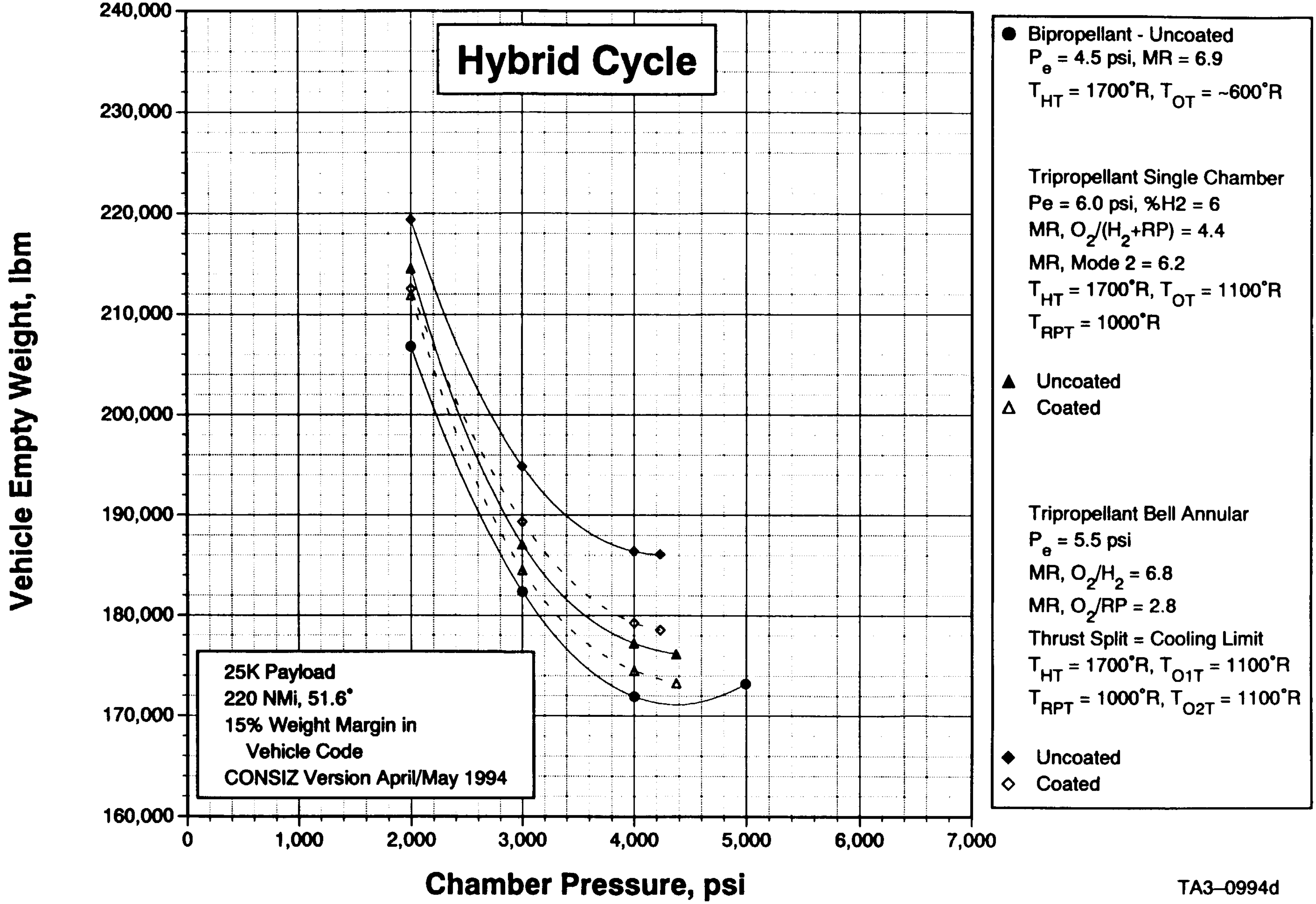

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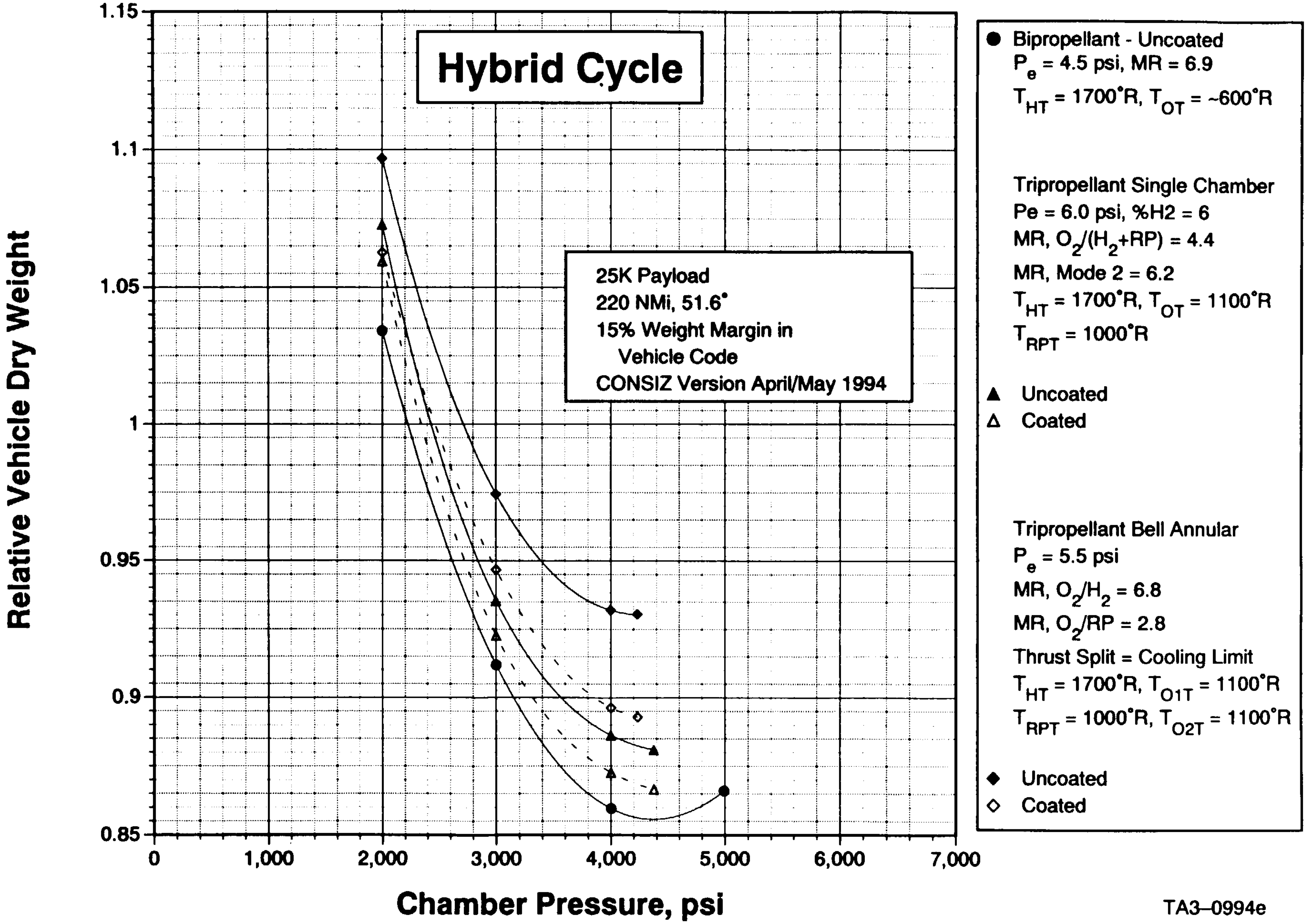


TA3–0994e

Tripropellant Comparison Study
Propellant Choice Observations

- Bipropellant and Tripropellant Vehicle Dry Weight Results Within 3% at All Chamber Pressures and All Cycles
  - Single Chamber Very Slightly Better Than Bell Annular (<3%)
  - Bipropellant Slightly Better Than Either Tripropellant

- **Tripropellant Has No Vehicle Performance Advantage Over Bipropellant**

TA3–1139

Reconciliation Between This Study and the Access-to-Space Results

TA3–0863p

From the Access-to-Space Report

WEIGHT GROWTH MARGIN GAINS (by technologies)

Chart Shows how much the dry vehicle weights produced by the use of each technology, could grow before reaching the Baseline value of 233K

$$Wt\ Baseline\ (SSME) = 233K = WT_{BL}$$

$$Wt\ Tripropellant = WT_{TP}$$

$$WT_{TP} \otimes (1+0.31) = WT_{BL}$$

$$WT_{TP} = WT_{BL}/1.31$$

$$= 178K$$

	Wt	Wt Difference from Baseline
SSME	233	—
Tri	178	23.6%

4200 psi, propane new engine } Tri

~~release~~

2800 psi, 25 yr old MR=6 engine } bi

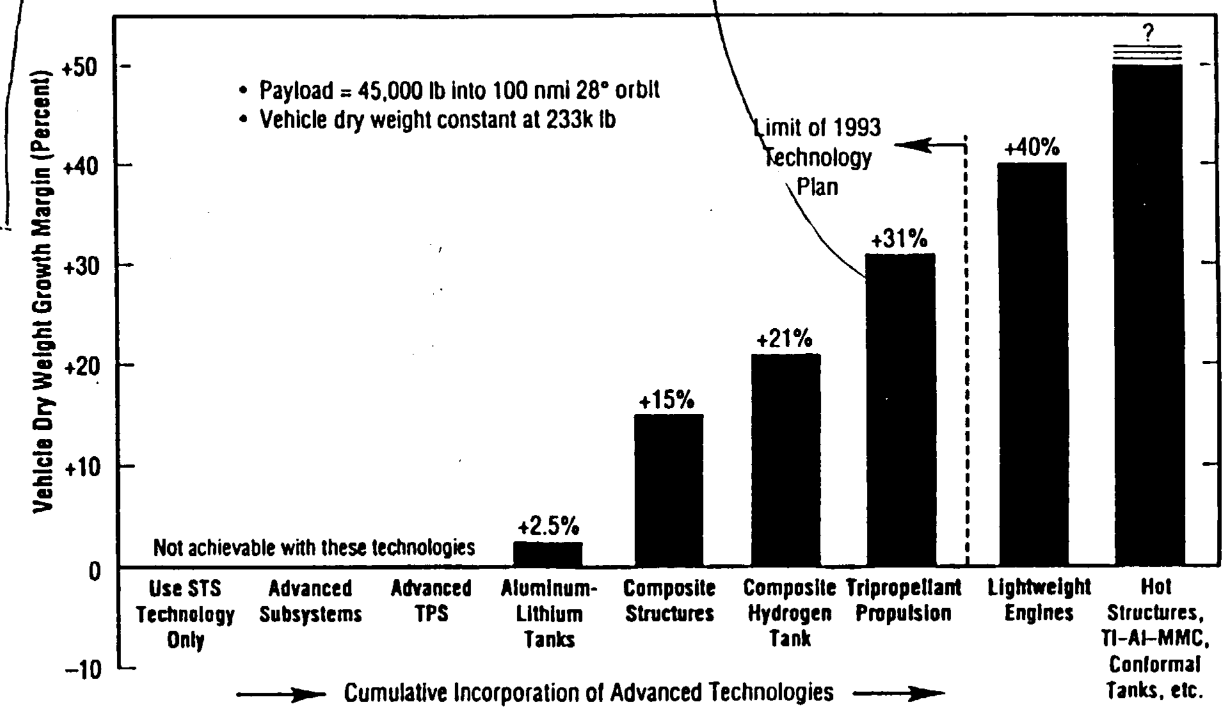


FIGURE 32.—Weight growth margin available.

Access to Space Study
Baseline Engines

- Bipropellant Engine
  - Modified SSME
    - Large Throat
    - Chopped Nozzle
      - Area Ratio = 50
    - MR = 6
    - Chamber Pressure = 2,800 psi
  - Conditions Far Off-Optimum for SSTO Mission
  - Essentially Existing Engine With Weights Known
  - 25 Year Old Design
  - Produced Dry Vehicle Weight of 233,000 lbm

- Tripropellant Single Chamber Engine
  - Chamber Pressure = 4,200 psi
  - Mode 1 MR = 4.4
  - Mode 2 MR = 6
  - Propellant Percentages = 81.5 O_2/ 6 H_2/ 12.5 RP
  - All At or Near Optimum for SSTO Mission
  - New Paper Engine - Weights Malleable
  - New Design
  - Produced Dry Vehicle Weight of 178,000 lbm
    - 23.6 % Lighter than Baseline Bipropellant Engine

TA3–1152

Access to Space Study

Bipropellant/Tripropellant Engine Reconciliation

- **Effect of Bringing Both Engines to Comparable Conditions**
  - **Same Chamber Pressure, Optimum MR's and Area Ratios, Same Design Groundrules and Practices and Technology Use**

	Change in Dry Vehicle Weight From Baseline of 233,000 lbm, Percent			
	Tripropellant	Bipropellant	Change	Cumulative Difference
Access to Space Study	—	—	—	23.6
Mode 2 MR (Tri – 6.2; Bi – 6.9)	-0.1	-3.7	-3.6	20.0
Chamber Pressure (4,000 psi)	+0.5	-5.2	-5.7	14.3
Both as New Engines Common Design Practices, Same Technologies	-6.9	-21.0	-14.1	0.2
He Usage	-0.0	-1.4	-1.4	-1.2

- **Essentially the Same — Excellent Agreement with Current Study**

TA3–1153

Tripropellant Comparison Study
Engine Cycle Margins

TA3–0863d

Alternate Propulsion Subsystem Concepts
Tripropellant Comparison Study
Margin Study

- Margins Studied
  - +5% Thrust
    - Chamber Pressure Increased
    - Nozzle Area Ratio Increased for Optimum Exit Pressure
  - 5:1 Throttling
    - LOX Cooled Nozzle
    - Kick Pump and RP Pump Fluids
      - 50% Preburner Injector Pressure Drop at Full Thrust
  - -5% All Turbopump Efficiencies
  - +10% Pump Discharge Pressures
  - All Margins Together

TA3-1140

Alternate Propulsion Subsystem Concepts
Tripropellant Comparison Study
Margin Study – Bipropellant Engines

	Baseline	+5% Thrust	5:1 Throttling	-5% TP Eff	+10% Pd's	All Margins
FFSCC-Bipropellant						
Engine Weight, lbm	4,567	4,809	4,688	4,738	4,796	5,308
Vehicle Dry Weight, lbm	181,105	180,264	183,492	184,494	185,670	189,843
Chamber Pressure, psi	4,000	4,187	4,000	4,000	4,000	4,187
Pump Discharge Pressure, psi						
Fuel	10,839	11,255	10,839	10,839	11,923	12,339
Oxidizer	9,889	10,304	10,356	9,889	10,878	11,760
Turbine Inlet Temperature, R						
Fuel	1,150	1,176	1,150	1,310	1,273	1,460
Oxidizer	1,100	1,100	1,100	1,110	1,104	1,385
SCC-Bipropellant						
Engine Weight, lbm	4,049	4,235	4,157	4,194	4,204	4,645
Vehicle Dry Weight, lbm	171,739	170,474	173,689	174,367	174,547	177,598
Chamber Pressure, psi	4,000	4,187	4,000	4,000	4,000	4,187
Pump Discharge Pressure, psi						
Fuel	11,673	12,128	11,673	11,673	12,840	13,295
Oxidizer	11,276	11,761	15,564	11,276	12,403	17,375
Turbine Inlet Temperature, R						
Fuel	1,400	1,400	1,400	1,540	1,498	1,800
Oxidizer	1,100	1,100	1,100	1,100	1,100	1,335

TA3–1141

Alternate Propulsion Subsystem Concepts

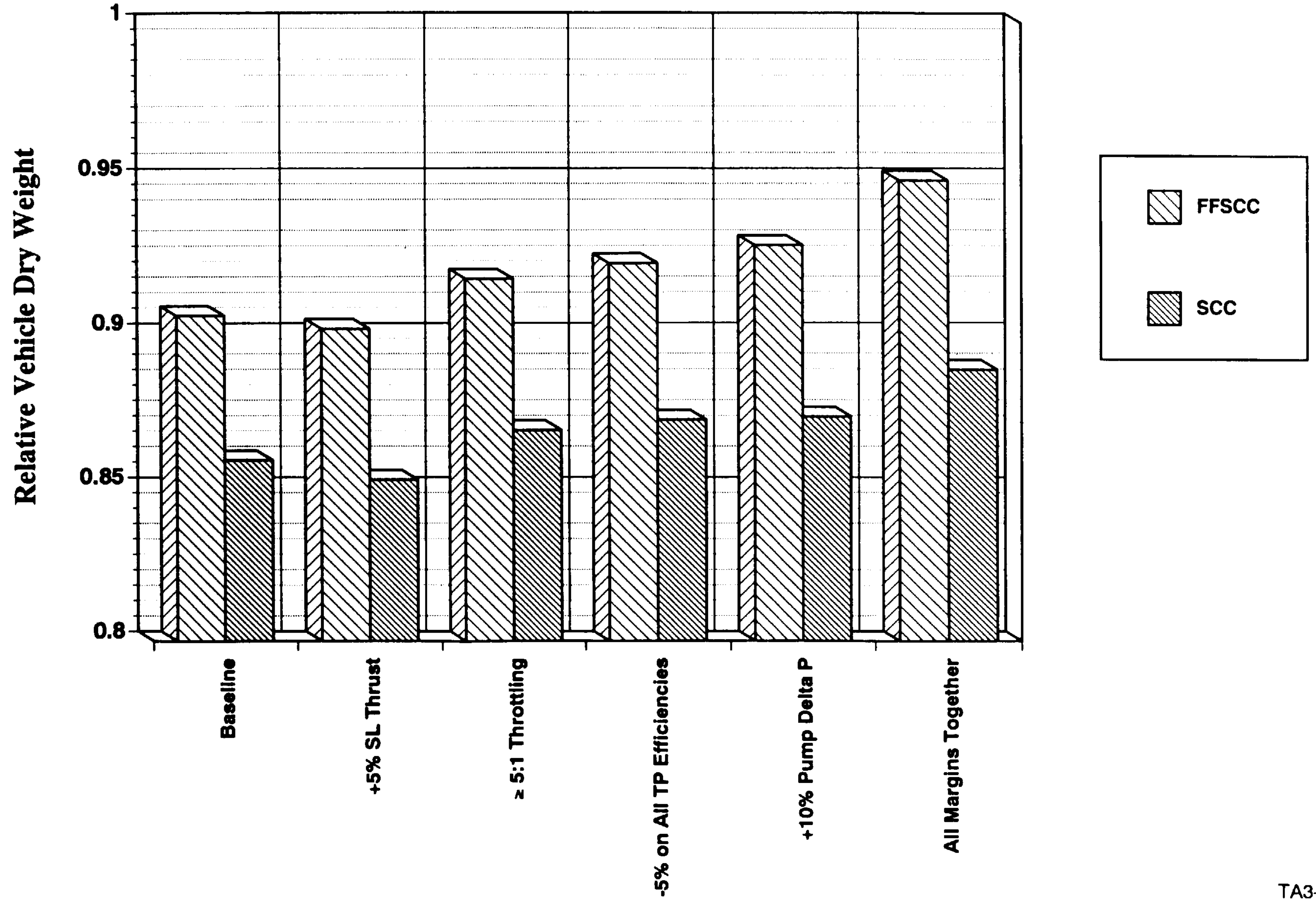
Tripropellant Comparison Study

Margin Study – Tripropellant Single Chamber Engines

	Baseline	+5% Thrust	5:1 Throttling	-5% TP Eff	+10% Pd's	All Margins
FFSCC-Tripropellant						
Engine Weight, lbm	4,492	4,735	4,660	4,614	4,667	5,253
Vehicle Dry Weight, lbm	184,144	183,188	187,853	186,824	188,011	194,352
Chamber Pressure, psi	4,000	4,187	4,000	4,000	4,000	4,187
Pump Discharge Pressure, psi						
Hydrogen	10,468	10,876	10,468	10,468	11,515	11,923
RP	9,023	9,417	12,529	9,023	9,925	13,988
Oxidizer	9,830	10,262	10,247	9,830	10,814	11,662
Turbine Inlet Temperature, R						
Hydrogen	1,150	1,150	1,150	1,254	1,217	1,447
RP	1,410	1,423	1,567	1,450	1,447	1,694
Oxidizer	1,100	1,100	1,100	1,100	1,100	1,303
FRSCC-Tripropellant						
Engine Weight, lbm	4,040	4,247	4,173	4,207	4,247	4,759
Vehicle Dry Weight, lbm	175,067	173,990	177,759	178,459	179,288	184,085
Chamber Pressure, psi	4,000	4,187	4,000	4,000	4,000	3,451
Pump Discharge Pressure, psi						
Hydrogen	10,822	11,247	10,822	10,822	11,904	10,657
RP	10,186	10,637	14,176	10,189	11,208	13,337
Oxidizer	10,200	10,648	14,187	10,200	11,221	13,350
Turbine Inlet Temperature, R						
Hydrogen	1,700	1,800	1,900	2,008	1,950	2,200
RP	1,700	1,800	1,900	2,008	1,950	2,200
Oxidizer	1,700	1,800	1,900	2,008	1,950	2,200

TA3–1142

Vehicle Dry Weight Sensitivity to Margin Requirements
Pc = 4,000 psi
Bipropellant Engines



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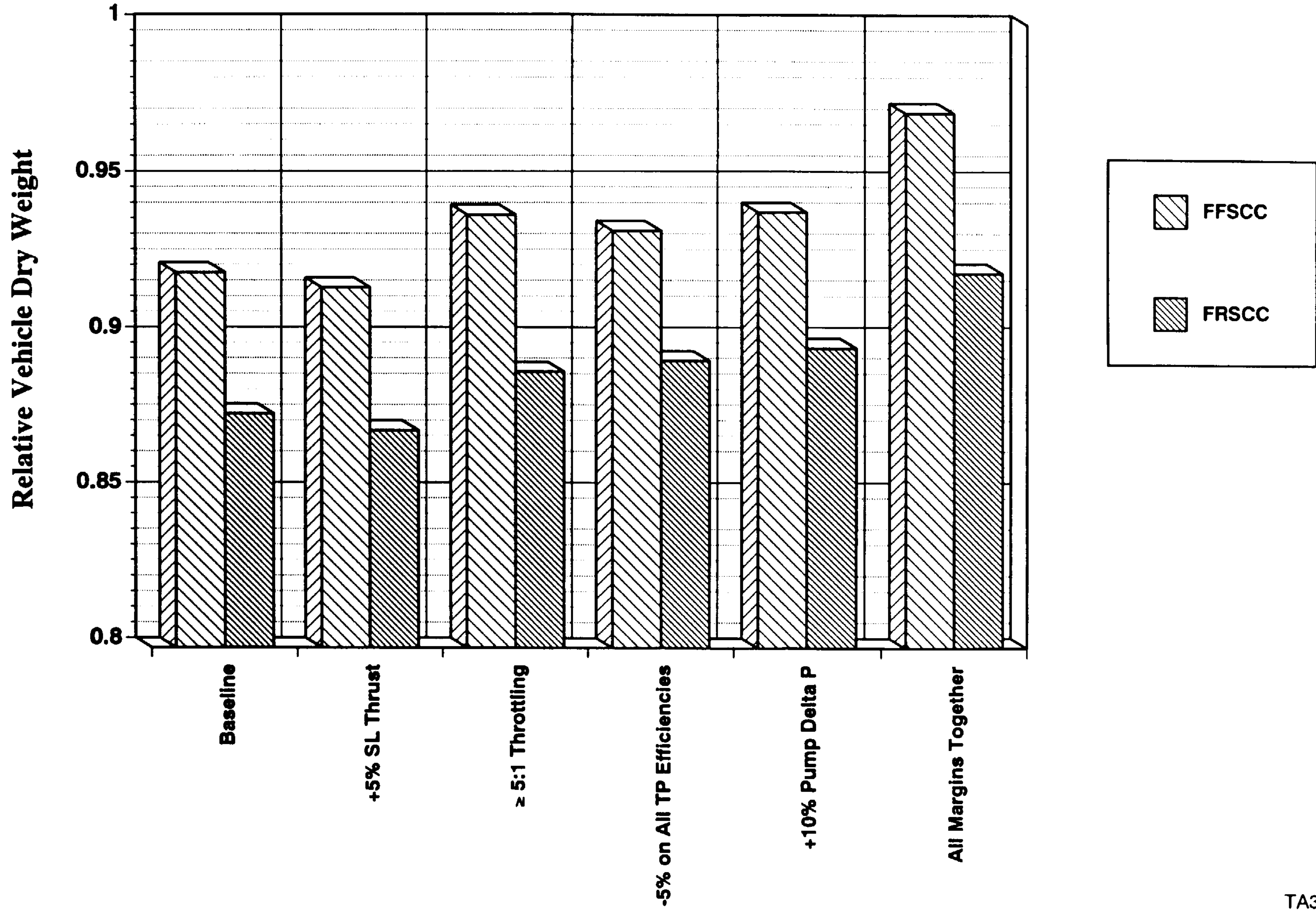
Vehicle Dry Weight Sensitivity to Margin Requirements
Pc = 4,000 psi
Single Chamber Tripropellant Engines



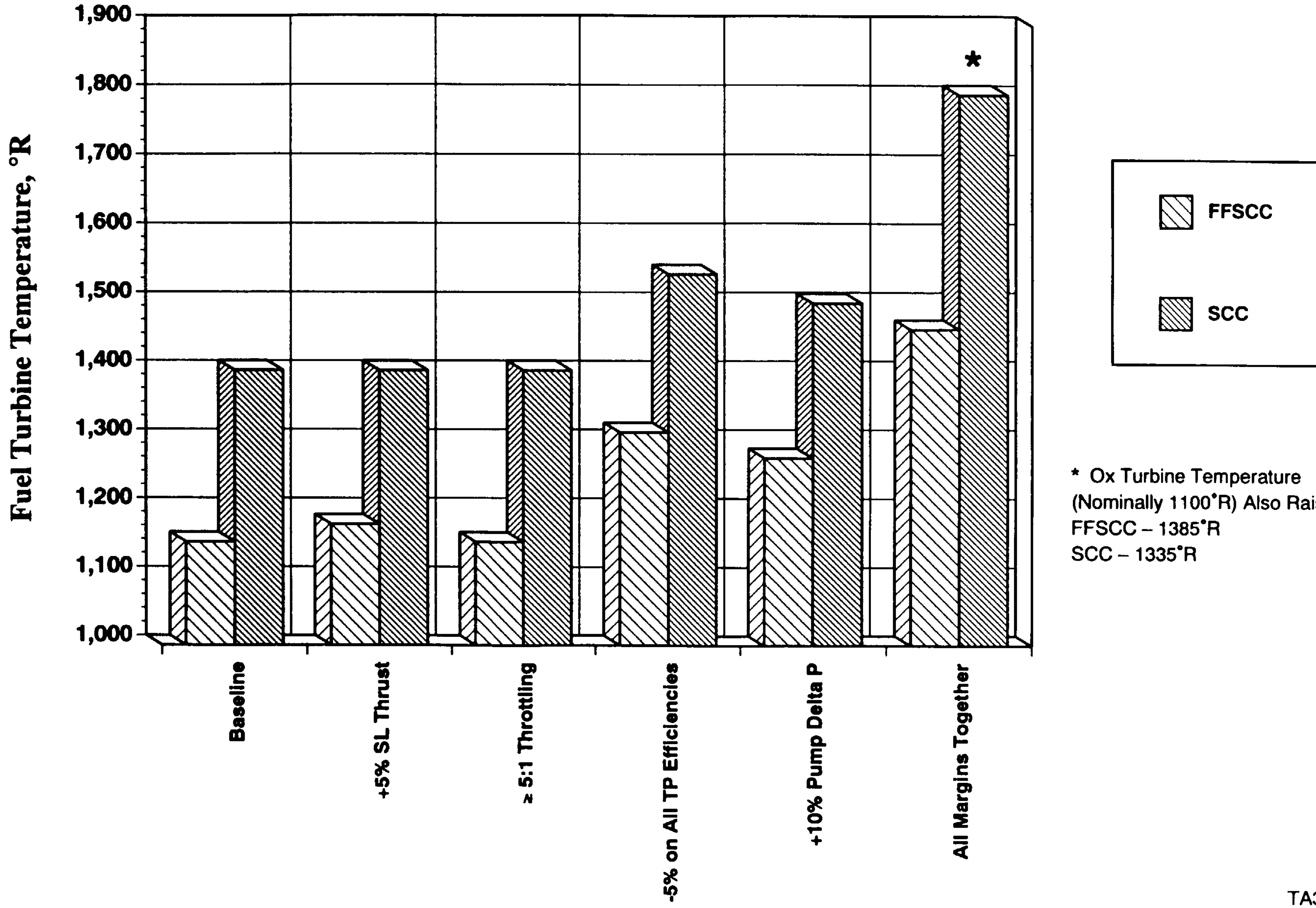
TA3–0907g

Turbine Operating Temperature as a Measure of Cycle Design Margin

- Margin can be Expressed in Terms of Turbine Inlet Temperature
  - Can be Increased to Increase Margin Where Desired or to Change Component Design Point Relationships
    - Thrust (Chamber Pressure)
    - Turbopump Parameters (Tip Speeds, Pitch-Line Velocities, Discharge Pressures, etc.)
    - Combustion Device Parameters (Throttling, Pressure Drops)
    - System Routing Pressure Drops
    - Weights (Line Pressure Drops, Nozzle Coolant Pressure Drops)
  - Full Flow Staged Combustion Cycle Turbine Inlet Temperature is More Robust than any Other Cycle
    - Max Power Possible
      - All Flow is Available for Power
      - Both Sides Add Chemical Energy

TA3–1126

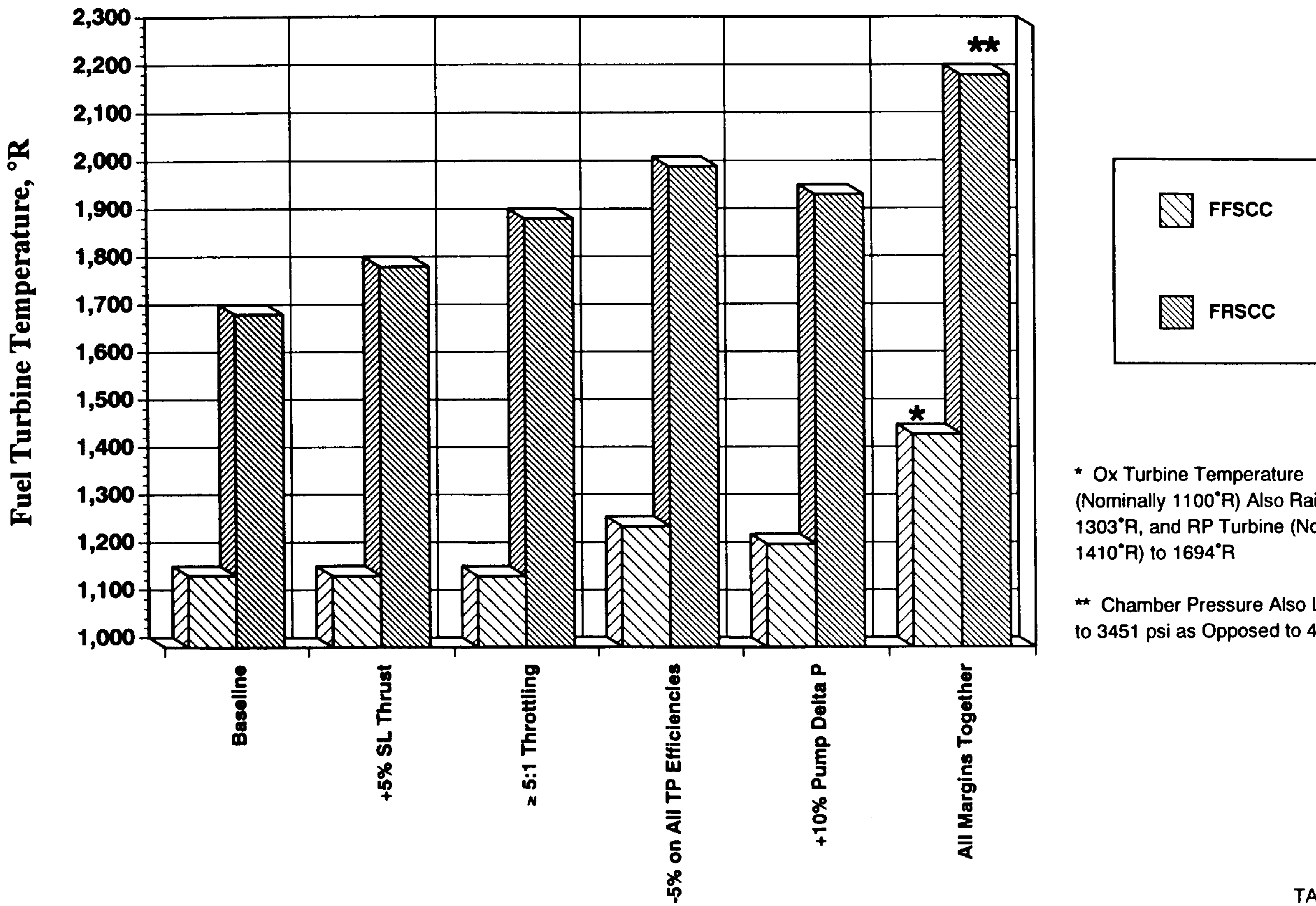
Fuel Turbine Temperature Sensitivity to Margin Requirements
Pc = 4,000 psi
Bipropellant Engines



* Ox Turbine Temperature (Nominally 1100°R) Also Raised to;
FFSCC – 1385°R
SCC – 1335°R

TA3–0907d

Hydrogen Turbine Temperature Sensitivity to Margin Requirements
Pc = 4,000 psi
Single Chamber Tripropellant Engines



* Ox Turbine Temperature (Nominally 1100°R) Also Raised to 1303°R, and RP Turbine (Nominally 1410°R) to 1694°R

** Chamber Pressure Also Limited to 3451 psi as Opposed to 4187 psi

TA3–0907e

Alternate Propulsion Subsystem Concepts

Tripropellant Comparison Study
Margin Study Observations

- Without Margin Considerations

  - FFSCC, SCC, and Hybrid Cycles are Comparable
    - At 4,000 psi and Below
    - All Cycles Except FFSCC At Least Marginal on Turbine Temperature to Avoid Cooled Powerhead

- With Margin Considerations

  - FFSCC is the Most Robust Cycle
    - Little Impact Except With All Margins
    - Still Uncooled Powerhead Even With All Margins

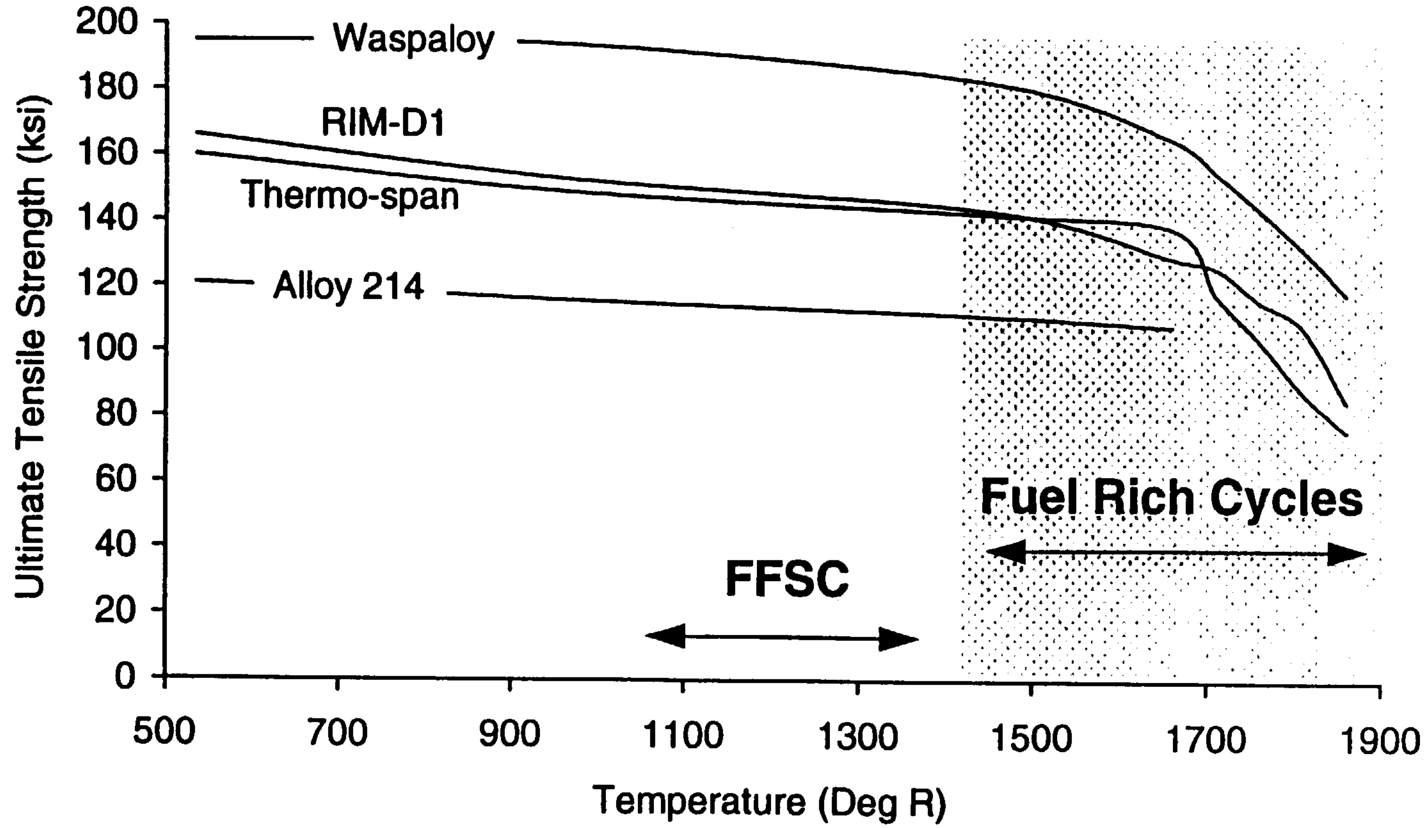
TA3–1143

Tripropellant Comparison Study
Conclusions

TA3–0863e

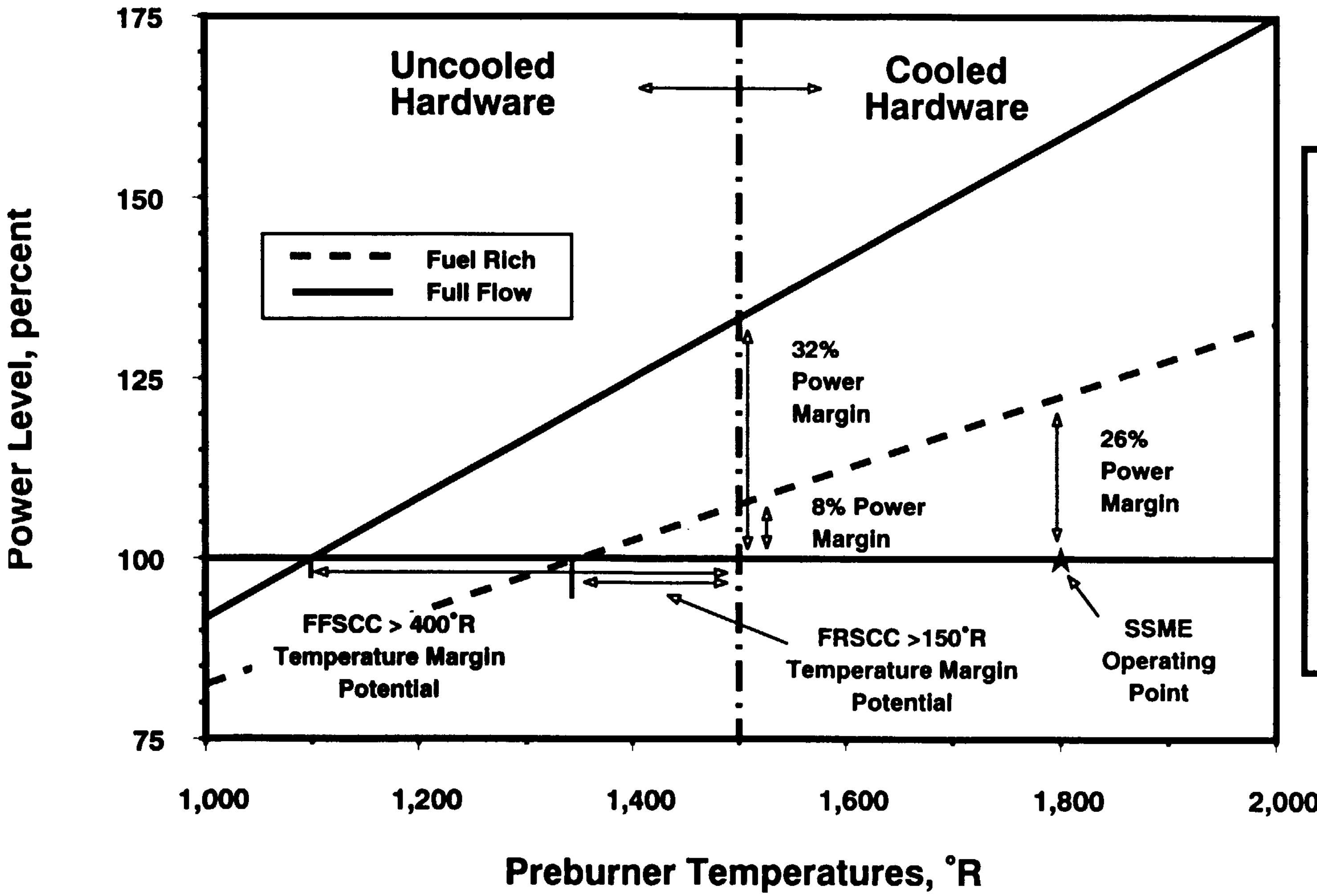
Cycle Choice Affects Life and Weight

- **Reduced turbine temperatures provide capability to accomodate engine / vehicle design uncertainties**
- **Fuel rich engine cycles operate near strength limits of available materials**



TA3–1128

Engine Cycle Choice Can Provide Increased Design Margins and Opportunity for Future Growth



Potential Margin Uses

- Design Maturation
- Increased MixtureRatio
- Increased Chamber Pressure
- Deep Throttling

TA3–0946

Tripropellant Comparison Study
Technology Implications

Technology Areas	Bipropellant	Tripropellant	Impact	Increase in Vehicle Dry Weight if Not Used
Increased P_c	X	X	Significant Weight Reductions Up to ~ 4,000 psi	
Improved Strength Oxygen Resistant Materials	X	X	Significant Weight Reductions in Cycles with Best Operating Margins	+3.0%
High Confidence, Long Life Coatings on the Ox Side	X	X	Significant Weight Reductions in Cycles with Best Operating Margins	+3.0%
Lower Turbine Operating Temperatures	X	X	Margin, Ops Costs	
LOX Rich LOX Turbopumps	X	X	Margin, Ops Costs Thru Lower Turbine Temperatures by Allowing Cycles Which are Less Sensitive in Turbine Operating Temperature versus ΔP, Throttling, and P_c	
LOX Rich Preburners	X	X		
SLIC™ Turbomachinery	X	X	Significant Weight Reductions, Better Ops	+7.5%
Jet Pumps	X	X	Significant Weight Reductions, Better Ops, Lower Costs	+5.8%
Vehicle Side Gimbal Flex Accommodation	X	X	Significant Weight Reductions on Engine	+1.9%
Al Fuel Pump	X	X	Lower Turbomachinery Weights	+1.2%
Laser Ignition	X	X	Easier Development, Better Ops	
Gasify LOX	X	X	Margin for Deep Throttling (e.g., 5:1)	
Health Monitoring/Life Prediction	X	X	Reliability, Ops Costs	

TA3–1144

Tripropellant Comparison Study Conclusions

- For Newly Designed Engines, Using the Same Groundrules and Technology
- No Significant Differences in Vehicle Dry Weight Performance Between Tripropellant and Bipropellant Engines
  - < 3 % Across Chamber Pressure Range 2,000-5,000 psi
    - Bipropellant Engine Slightly Better
  - Single Chamber and Bell Annular Tripropellant Configurations Similar in Vehicle Performance (< 1 %)
- Much Larger Vehicle Performances Differences Within Any One Engine Configuration Due to Operating Point and Design Choices
  - Mixture Ratio
  - Chamber Pressure
  - Nozzle Exit Pressure
  - Power Cycle
  - Coated versus Uncoated Materials
  - Welded versus Cast
- FFSCC Has Significantly Higher Available Margins Than Staged Combustion Cycle (SCC)
  - For Both Bipropellant and Tripropellant Engines
    - Differences More Pronounced for Tripropellant Engines
  - Inherent Engine Weight Difference ~ 2-5%
    - Favors SCC
    - Applies if Coated Ox Side Or Improved Ox Resistant Materials
  - Strongly Supports the Value of Ox Resistant Material Technology Programs

TA3–1135b

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13. ABSTRACT *(Maximum 200 words)*

A study was conducted under MSFC contract NAS8-39210 to compare tripropellant and bipropellant engine configurations for the SSTO mission. The objective was to produce an "apples-to-apples" comparison to isolate the effects of design implementation, designing company, year of design, or technologies included from the basic tripropellant/bipropellant comparison. Consequently, identical technologies were included (e.g., jet pumps) and the same design groundrules and practices were used. Engine power cycles were examined as were turbomachinery/preburner arrangements for each cycle. The bipropellant approach and two tripropellant approaches were separately optimized in terms of operating parameters: exit pressures, mixture ratios, thrust splits, etc.

This briefing presents the results of the study including engine weights for both tripropellant and bipropellant engines; dry vehicle weight performance for a range of engine chamber pressures; discusses the basis for the results; examines vehicle performance due to engine cycles and the margin characteristics of various cycles; and identifies technologies with significant payoffs for this application.

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